

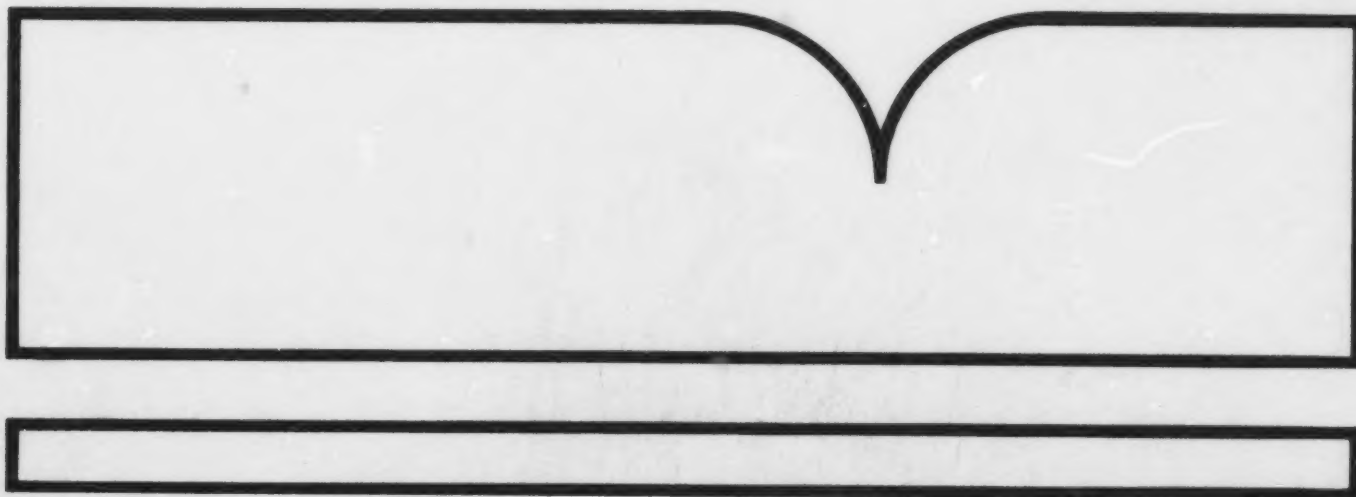
On-Site Meteorological Instrumentation
Requirements to Characterize Diffusion from
Point Sources: Workshop Report

Environmental Research and Technology, Inc.
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On-Site Meteorological Instrumentation Requirements to Characterize Diffusion from Point Sources

Workshop Report

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ON-SITE METEOROLOGICAL INSTRUMENTATION REQUIREMENTS
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Workshop Report

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ABSTRACT

Results of a workshop entitled "On-Site Meteorological Instrumentation Requirements to Characterize Diffusion from Point Sources" are summarized and reported. The workshop was sponsored by the U.S. Environmental Protection Agency in Raleigh, North Carolina, on January 15-17, 1980. Its purpose was to provide EPA with a thorough examination of the meteorological instrumentation and data collection requirements needed to characterize airborne dispersion of air contaminants from point sources and to recommend, based on an expert consensus, specific measurement techniques and accuracies. Secondary purposes of the workshop were to (1) make recommendations to the National Weather Service (NWS) about collecting and archiving meteorological data that would best support air quality dispersion modeling objectives and (2) make recommendations on standardization of meteorological data reporting and quality assurance programs.

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SYMBOLS AND ABBREVIATIONS

c	Pollutant concentration
c_p	Specific heat of air
$d\theta/dz$	Wind direction shear with height
e_w	Water vapor pressure
g	Acceleration due to gravity
h	Surface layer depth
h_c	Convective mixing depth
h_m	Mechanical mixing depth
h_0	Average height of roughness elements
k	von-Karman constant
n	Frequency in cycles per unit time
u, v, w	Orthogonal wind speed components
$\bar{u}; \bar{u}_v, \bar{u}_s$	Mean wind speed; vector, scalar
u_*	Friction velocity
w_*	Convective velocity scale
z_0	Surface roughness length scale
z_{0e}	Effective surface roughness length scale
C_D	Drag coefficient
C_T^2	Temperature structure parameter
C_v^2	Velocity structure parameter
D	Thermal diffusivity
Fr	Froude number
H_F	Surface heat flux
K_m, K_H	Turbulent momentum and heat exchange coefficients
L	Monin-Obukhov length scale

SYMBOLS AND ABBREVIATIONS

Q_m	Maximum surface temperature flux
Q_0	Surface temperature flux
Q^*	Radiant flux density
R_c	Climatological representativeness
R_p	Primitive representativeness
R_s	Spatial representativeness
Ri_B	Bulk Richardson number
Ri_f	Flux Richardson number
Ri_Δ	Gradient Richardson number
T	Temperature
T_d	Dew point temperature
T_s	Surface layer temperature scale
X_Θ	Temperature dissipation length
$\Delta T/\Delta Z$	Temperature gradient over a layer
ϵ	Eddy dissipation rate
θ	Wind direction
Θ	Potential Temperature
λ	Area density of roughness elements
ρ	Density of air
σ_T	Standard deviation of temperature
σ_y, σ_z	Horizontal and vertical plume spread parameters
$\sigma_\theta, \sigma_v, \sigma_u$	Standard deviation of azimuthal wind direction/wind speed components
σ_ϕ, σ_w	Standard deviation of elevation angle/vertical speed components

SYMBOLS AND ABBREVIATIONS

$\sigma(1/u)$	Standard deviation of the reciprocal of wind speed fluctuations
τ	Reynolds shear stress
SBL	Surface boundary layer
PBL	Planetary boundary layer

ACKNOWLEDGEMENTS

This workshop was sponsored by the U.S. Environmental Protection Agency under Contract 68-02-3282, administered by D. Bruce Turner, John Irwin, and William Petersen of the EPA Division of Meteorology.

Many individuals contributed to the content of this report during the course of the workshop. The authors are especially indebted to Dr. Todd Crawford, Maynard Smith, and Thomas Lockhart, the three panel chairmen, for their efforts in collecting, organizing, and integrating the conclusions and recommendations of their panels. Their panel reports form the basis of this document.

We give special thanks to Dr. Frank Pasquill, a consultant to ERT, for his active participation in the workshop and his assistance in reviewing and distilling the workshop findings.

1. INTRODUCTION

A workshop entitled "On-Site Meteorological Instrumentation Requirements to Characterize Diffusion from Point Sources" was held in Raleigh, North Carolina, on January 15-17, 1980. The workshop was sponsored by the U.S. Environmental Protection Agency (EPA) and arranged by Environmental Research & Technology, Inc. The purpose of the workshop was to provide EPA with a thorough examination of the meteorological instrumentation and data collection requirements needed to characterize airborne dispersion of air contaminants from point sources, and to recommend, based on an expert consensus, specific measurement techniques and accuracies. Secondary purposes of the Workshop were to (1) make recommendations to the National Weather Service (NWS) about collecting and archiving meteorological data that would best support air quality dispersion modeling objectives and (2) make recommendations on standardization of meteorological data reporting and quality assurance programs.

A representative group of 31 scientists drawn from regulatory agencies, industries, universities, research laboratories, and consulting firms participated in the workshop. The workshop was conducted in three panels for the majority of its work, with plenary sessions for coordination.

- Panel A, chaired by Maynard Smith, evaluated Data Requirements, including model input variables, data representativeness, accuracy requirements, averaging and sampling periods, data archiving, and recommendations to the NWS.
- Panel B, chaired by Todd Crawford, considered the computations and data required for Derived Variables used to describe turbulence and diffusion in the planetary boundary layer.
- Panel C, chaired by Tom Lockhart, reviewed measurement techniques for the requisite Meteorological Variables.

Summary reports from each of these panels have been integrated as the basis of the workshop recommendations. The individual panel reports by the panel chairmen are included as working papers in the appendices. As such, they have undergone minimum editing.

Meteorological measurements discussed by the workshop are used in point source diffusion modeling and in analysis of air quality monitoring data (e.g., as discussed in the Modeling Guideline [EPA 1978a] and the Monitoring Guideline [EPA 1978b]). The workshop recommendations are intended to help the modeler choose the instrumentation and analysis techniques required to measure accurately the variables needed for his model rather than to help him choose the "best" model. Most variables previously found useful for dispersion modeling were considered, and reasonably attainable accuracies were estimated.

The meteorological variables were divided into three priority classes: (1) essential, (2) desirable, and (3) helpful. These classes reflect a judgment about desirable progress in state-of-the-art modeling and should not limit the modeler in selecting the variables for specific applications.

The workshop results de-emphasize relying on the Pasquill-Gifford-Turner (PGT) stability classification as a primary means of characterizing atmospheric diffusion; rather they emphasize relying upon on-site measurements of turbulence intensity to characterize the dispersion properties of the atmosphere. This is a major step forward from the assumptions of many models currently used in air pollution control evaluation. Of course, much model testing and evaluation will be required before the PGT classification scheme can be replaced. The workshop, however, felt that modeling could be advanced by using these variables in the priorities assigned. These workshop recommendations do not constitute EPA policy with regard to meteorological monitoring programs.

Variables contained in each priority set are addressed, in turn, in Sections 2 through 4, which describe explicitly the relationships between the recommended modeling variables and the required measurements. Section 5 is the Panel A report on recommended changes in NWS data collection. Section 6 is the Panel A report on data archiving and retrieval. The list of participants is presented in Section 7.

2. ESSENTIAL (PRIORITY 1) MEASUREMENTS

The quantities that have been identified as essential to further progress in atmospheric dispersion modeling are:

- mean horizontal wind speed ($\bar{u}$) and mean wind direction ($\bar{\theta}$) at 10 meters (m),
- mean horizontal wind speed and mean wind direction at source height,
- harmonic mean wind speed $(1/\bar{u})^{-1}$ between source height and effective plume height,
- standard deviations of horizontal and vertical wind fluctuations (e.g., σ_θ , σ_ϕ) at 10 m,
- temperature difference (ΔT) between 2 and 10 m in unobstructed surface layers,
- temperature (T) at 2 m,
- heights of the convectively mixed layer (h_c) and the mechanically mixed layer (h_m),
- average surface roughness length (z_0),
- friction velocity (u_*),
- bulk Richardson number (Ri_B),
- Monin-Obukhov length scale (L),
- turbulent heat flux (H_F),
- convective velocity scale (w_*), and
- the water vapor content (e_w) between source height and effective plume height (if the water content of source emissions is important).

Some of these quantities are primary—direct averages or statistical evaluations of direct measurements—while others are derived from combinations of the primary quantities.

Wind Measurements

For horizontal wind speed, the scalar mean ($\bar{u}_s$) and the resultant vector mean ($\bar{u}_v$) should be reported. The harmonic mean

($\bar{u}_h$) is, however, preferred for calculating initial dilution and plume rise. These variables are defined by

$$\begin{aligned}\bar{u}_s &= \frac{1}{N} \sum_{i=1}^N u_{s_i} \\ \bar{u}_v &= \left[\left(\frac{1}{N} \sum_{i=1}^N u_i \right)^2 + \left(\frac{1}{N} \sum_{i=1}^N v_i \right)^2 \right]^{1/2} \\ \bar{u}_h &= \left(\frac{1}{N} \sum_{i=1}^N \frac{1}{u_{s_i}} \right)^{-1}\end{aligned}$$

Mean wind direction should be reported as the hourly resultant vector direction ($\bar{\theta} = \arctan \bar{v}/\bar{u}$). Satisfactory measurements of wind speed and wind direction can be made with cup anemometers and wind vanes, with wind vanes and front-mounted propeller anemometers, or with two or three propellers mounted on orthogonal axes (three propellers to include vertical wind velocity).

The standard deviations of wind fluctuations ($\sigma_\theta, \sigma_\phi$ or $\sigma_u, \sigma_v, \sigma_w$) should be calculated directly, not by a range estimator. For sufficient accuracy (~5%), the computation should be based on digital or mathematically equivalent analog techniques.

At monitor sites likely to experience intermittent pollutant concentrations, wind statistics based on a 3-minute sampling duration (or shorter) for σ_θ should also be gathered. These σ_θ values can then be combined to match pollutant release intervals in order to model time-integrated concentration fields.

Cup or propeller anemometers must be accurate to within 0.2 m/s +5% of the wind speed, with a start speed of ≤ 0.5 m/s, and a distance constant (63% recovery) of ≤ 5 m. Wind vanes must have a resolution of 1° and an accuracy of 5° . Delay distance (50% recovery) must be ≤ 5 m with a damping ratio of ≥ 0.4 .

Sixty or more samples will estimate hourly means to within 5-10%. Sample averaging time should be 1-5 seconds, with a response time of 1 second. Three hundred and sixty or more samples will estimate the hourly standard deviation within 5-10%. The need for 360

samples for calculating hourly standard deviations was questioned during post-workshop discussions. The response from Panel C members stated that 360 samples is a conservative number based on substantial experience. In some instances fewer samples would be needed, but there is no general guide for identifying those situations prior to sampling.

Applied techniques for obtaining winds aloft include tracking superpressure balloons, and using Doppler sodar systems.

Ascending free balloons provide data on flow trajectories over a finite time interval. Since the balloon does not exactly follow an air parcel when vertical motion is involved, the results must be interpreted cautiously.

The Doppler sodar technique may be used in either the monostatic or bistatic mode. Measurements of wind components aloft are accurate to about 0.5 m/s. These measurements routinely provide information to heights of 500 m, and sometimes to heights above 1,000 m.

Temperature Measurements

Ambient air temperature should be measured at 2 m, consistent with the World Meteorological Organization (WMO) standards for ambient temperature measurements. It is recognized that some derived parameters are based on temperatures at 10 m, but this value may be calculated from the 2 m temperature and the 2-10 m temperature difference. The ambient temperature measurement should be accurate to 0.5°C, with a resolution of 0.1°C.

Temperature differences should be measured between 2 and 10 m in an unobstructed surface layer. Measurements should be made with an independent probe system that makes no reference to other measurements of ambient temperature or to the standard deviation of temperature fluctuations (σ_T). Properly shielded and aspirated, a temperature probe system can attain 0.1°C accuracy, and 0.02°C resolution within the present state-of-the-art. Standards of probe selection, calibration, and maintenance for research efforts can yield 0.05°C accuracy, and 0.01°C resolution. The time constant (63%) of the

temperature probe should be 1 minute, and the sample averaging time should be greater than or equal to half the time constant.

In siting the probes, care must be taken to maintain the integrity of the ambient environment, particularly the surface, in the immediate vicinity of the tower. This is especially important for temperature probes 2 m above the ground. Site preparation usually requires substantial modification of the surface at a monitoring site. Panel C did not make specific recommendations about site preparation techniques to insure representative measurements.

It is recognized that 0.1°C accuracy is insufficient for distinguishing atmospheric stability in some applications. Greater accuracy is needed to enhance the usefulness of temperature difference measurements.

Mixed Layer Heights

Mixed layers may be maintained convectively by surface heating or maintained mechanically by wind-generated turbulent mixing. A mixed layer is classified as either convective or mechanical as one or the other mechanism is dominant. When both mechanisms are active, the buoyancy driven mixed layer usually dominates.

The convective layer height (h_c) should be measured routinely by a monostatic sodar with vertical beam. Objective rules have been developed to assist the operators in evaluating h_c , and automatic and pattern recognition methods are under development. Sodars resolution is about 10 m, and the useful range varies from 50 to 1,000 m. The sampling time constant is typically 10 seconds. Convective mixed layer heights derived from sodar and from rawinsonde profiles generally agree to within 50 m.

When the mixed layer height exceeds the range of the sodar system, other methods are available. Aircraft equipped with a fast response temperature sensor readily provide temperature profiles to greater heights. Tethersondes may be used in moderate to light wind conditions where they are not an aviation hazard. A slow-rise radiosonde balloon may be used when tracked by double theodolite observations. These tracked balloons also provide data on winds aloft.

Bistatic sodar can be used to derive the mechanically mixed layer height, h_m , in the stable boundary layer. But the method is of limited value because the characteristic value of h_m lies between 0 and 200 m, while the minimum range of the technique is 50 m. The mechanically mixed layer height is best measured with temperature or velocity turbulence data from an instrumented tower, supported by sodar.

Roughness Length

The roughness length (z_0) at a site may be derived from wind speed profile data under neutral atmospheric conditions or estimated from a description of surrounding surface features. Once estimated, the roughness length may be assumed to be fixed. Consequently, only a limited record of wind profile data is needed.

If z_0 is to be derived from wind profile data over relatively flat, homogeneous terrain, wind measurements should be made at three heights between 2-20 m, most desirably with 5% wind speed accuracy, 10-second response time, 30-second sample averaging time, and 1-hour sampling duration. If, however, the surface is patchy with large and varied roughness elements so that it is difficult to determine the proper instrument heights, z_0 can be estimated indirectly and z_0 values should depend upon wind direction. The estimate should take into account the size and distribution of roughness elements. Several methods for estimating z_0 were referenced by Panel B, but none has been shown to be completely satisfactory. Fortunately, dispersion modeling is not very sensitive to z_0 . It is adequate to estimate z_0 to within a factor of 2.

Bulk Richardson Number, Friction Velocity, Monin-Obukhov Length, Heat Flux, and Convective Velocity

The derived quantities Ri_B , u_* , L , H_p , w_* can be estimated from temperature and wind measurements.

The bulk Richardson number, Ri_B , is derived from measurements at 2 m and 10 m:

$$Ri_B = \frac{g \cdot (z_{10})}{T_{10}} \frac{(\Delta T + \Gamma)}{(\bar{u}_{10})^2}$$

where g is the acceleration due to gravity, T_{10} ($^{\circ}K$) is the ambient temperature at 10 m, and Γ is the dry adiabatic lapse rate. This value of Ri_B is representative of the surface boundary layer only.

The Monin-Obukhov length scale, L , may be evaluated indirectly from the value obtained for Ri_B . Assuming the validity of surface layer similarity theory relationships, L can be obtained by iterative approximation to:

$$\frac{z}{L} = Ri_B \frac{k F^2}{G}$$

where F and G represent integral forms of the empirical flux-profile relations (Benoit 1977, Irwin and Binkowski 1980). Both F and G are functions of z/z_0 , z/L , and z_0/L . Since the bulk Richardson number is derived from measurements at 2 m and 10 m, z in this application is 10 m. This procedure for obtaining L has been compared with direct measurement results, and shown to be within a factor of 2.

The surface friction velocity u_* is readily calculated once L is derived. By definition, the function F , used in the iterative technique for obtaining L from profile measurements, is the ratio of the mean wind at the upper measurement height (10 m) to the friction velocity. Therefore

$$u_* = \frac{\bar{u}(z_{10})}{F(z_{10}/z_0, z_{10}/L, z_0/L)}$$

Similarly, the surface heat flux H_F is calculated from L and u_* . Using the definition of the Monin-Obukhov length,

$$H_F = -u_*^3 \rho C_p T_{10} / (k g L)$$

Finally, the convective velocity scale, w_* , is derived from the heat flux and the convective layer height, h_c by:

$$w_* = \left(\frac{g}{T_{10}} \frac{H_F}{C_p} h_c \right)^{1/3}$$

Measurements of incoming solar radiation or net radiation can also be used to estimate w_* (Venkatram 1978, Briggs 1975).

Water Vapor Content Measurements

Water vapor content, e_w , is derived in part from measurements of temperature dew point, T_d . Either of two dew point sensor techniques may be used: the dew cell technique or the cooled-mirror technique. A measurement accuracy of $\pm 1.5^\circ\text{C}$ over the temperature range -30° to $+20^\circ\text{C}$ is adequate. As a rule, the time constant of the system is not critical—1 to 30 minutes. For some applications such as cooling tower fog formation, a short time constant may be required.

The dew cell technique with a resistance thermometer element has a characteristic time constant of 12-15 minutes; miniature versions with thermistors are much faster. For measurements at source height or above, it is important to measure the corresponding ambient temperature so that the water vapor content of the air may be calculated.

Summary

The basic measurements required for Priority 1 quantities are presented in Table 2-1 with information on instrument heights, accuracy, resolution, sampling times, and response time.

TABLE 2-1
MEASUREMENTS REQUIRED FOR PRIORITY 1 VARIABLES

Measurement	Height	Accuracy	Resolution	Sample Averaging Time	Response Time
u^+	10 m, source, plume	0.2 m/s + 5%	-	1-5 seconds	Distance Const $\leq 5m$
θ^+, ϕ^+	10 m, source	0.5 m/s	-	-	-
ΔT	2-10 m	Absolute 5° Relative 1°	-	1-5 seconds	Distance Const $\leq 5m$ Damping Ratio > 0.4
h_c	50-2,000 m	0.1C	0.02C	30 seconds	1 minute
h_m	0-200 m	50 m	10 m	-	10 seconds
T_d^{++}	source, plume	10-50 m	10 m	-	10 seconds
		1.5C	0.1C	$\geq 1/2$ of response time	1-30 minutes
T	2 m, source, plume,	0.5C	0.1C	30 seconds	1 minute

⁺Or equivalent wind measurements u, v, w. Requirements specified are for threshold speeds ≤ 0.5 m/s.
⁺⁺Required only when cooling tower plumes are modeled.

All the derived quantities depend, ultimately, on the primary measured quantities; some derived quantities depend on others derived first. Table 2-2 lists all the Priority 1 quantities, the time intervals for their characterization, and the quantities from which they are determined.

TABLE 2-2
INTERDEPENDENCE OF PRIORITY 1 VARIABLES

Symbol	Sampling Duration	Needed for Derivation	Comments
$\bar{u}_v, u_s$	1 hr	$u, \theta: 10 \text{ m, source}$	-
$\bar{\theta}_v$	1 hr	$u, \theta: \text{source}$	-
$\bar{l}/u_s$	1 hr	$u: \text{source}$	1-min samples of u
$\sigma_\theta, \sigma_\phi$	1 hr	$\theta: 10 \text{ m}$	-
	3 min	$\theta: 10 \text{ m}$	Optional, depending on source characteristics
ΔT	1 hr	$\Delta T: 2-10 \text{ m}$	-
h_c	1 hr	h_c	-
h_m	1 hr	h_m	-
z_0	1 hr	$u: 2 \text{ m, } 10 \text{ m, } 20 \text{ m}$	Derived from wind profile measurements or estimated from site description.
Ri_B	1 hr	$\Delta T, \bar{u}(10 \text{ m}), T(2 \text{ m})$	-
L	1 hr	Ri_B, z_0	-
u_*	1 hr	$z_0, \bar{u}(10 \text{ m}), L$	-
H_F	1 hr	$\Delta T, L, u_*, T(2 \text{ m})$	-
u_*	1 hr	$H_F, T(2 \text{ m}), h_c, \Delta T$	-
e_v	3 hr	$T_d, T: (\text{source})$	-

3. DESIRABLE (PRIORITY 2) MEASUREMENTS

In addition to the Priority 1 variables, six other variables were recommended as desirable for more accurate modeling in certain situations:

- standard deviation of the reciprocal of the wind speed at source height ($\sigma(1/u)$),
- mean wind direction at plume height ($\bar{\theta}_v$),
- standard deviation of horizontal and vertical wind fluctuations at source height ($\sigma_\theta, \sigma_\phi$),
- temperature gradient from source height to effective plume height (ΔT), and
- solar radiation (SR).

Wind Measurements

The Priority 1 wind measurements at source height will provide the data necessary to estimate $\sigma(1/u)$, σ_θ , and σ_ϕ at source height. Remote sensing or tall tower observations of u and θ are required for $\bar{\theta}$ at plume height.

Computational procedures and sampling duration for $\sigma(1/u)$ are similar to those for σ_θ and σ_ϕ already discussed in Section 2. It is recommended that the standard deviation for $\sigma(1/u)$ be computed from 1-minute averages of $\bar{u}$ to retain only the lower frequency variations in wind speed which affect plume rise.

Temperature Measurements

For sources of modest effective plume height, the temperature gradient from source height to plume top may be obtained from an instrumented tower, with measurement accuracies of 0.1°C . For tall sources, discrete temperature sounding profiles are accurate enough to resolve major temperature gradients through the layer of plume rise. Such temperature profiles, obtained once per hour, will also help resolve h_m and h_c .

Solar Radiation

Global sun and sky radiation should be measured with pyranometers with 50 W/m^2 accuracy, a resolution of 10 W/m^2 , and time constant (63%) of about 5 seconds. A complementary net radiometer may have a response time between 0.5 and 1.0 minute. Radiation measurements may be used to estimate w_* .

Summary

Six additional modeling variables are desirable. Their derivations require measurements of winds aloft (at plume height), of temperature profiles to plume heights, and of solar radiation (SR) measurements at the surface. Table 3-1 lists the Priority 2 variables, the time interval for characterization, and the quantities from which they are immediately determined.

TABLE 3-1
DEPENDENCE OF PRIORITY 2 VARIABLES ON MEASUREMENTS

<u>Quantity</u>	<u>Sampling Duration</u>	<u>Derivation</u>	<u>Comments</u>
$\sigma(1/u)$	1 hr	u:source	1-min averages of $\bar{u}$
$\bar{\theta}_v$	1 hr	u, θ :plume	-
$\sigma_{\theta}, \sigma_{\phi}$	1 hr	θ, ϕ :source	-
	3 min	θ, ϕ :source	Optional, depending on source characteristics
ΔT	1 hr	ΔT :source-plume	Vertical profile
SR	1 hr	$Q^*:1\text{ m}$	Total solar and net radiation

4. HELPFUL (PRIORITY 3) MEASUREMENTS

Several further variables are helpful when modeling in complex terrain or when considering long-range transport. These include the mean vertical velocity ($\bar{w}$), the Froude number (Fr), the geostrophic wind (U_g), and the state of the ground over which the plume travels. $\bar{w}$ requires measurements of vertical velocity and Fr requires vertical profiles of temperature and velocity to heights exceeding local terrain elevation. Geostrophic winds should be calculated from three-hourly NWS observations near the site. Table 4-1 summarizes the Priority 3 variables.

TABLE 4-1
DEPENDENCE OF PRIORITY 3 VARIABLES ON MEASUREMENTS

<u>Quantity</u>	<u>Sampling Duration</u>	<u>Derivation</u>	<u>Comments</u>
$\bar{w}$	1 hr	$w:10\text{ m}$	Useful for complex terrain modeling
Fr	1 hr	$\Delta T, u:\text{Profile}$	Useful for complex terrain modeling
U_g	3 hr	NWS P, T	Useful for long range transport modeling
State of the Ground	3 hr	Observation	-

5. RECOMMENDATIONS FOR THE OFFICE OF THE FEDERAL COORDINATOR FOR METEOROLOGY

Translating the recommendations of this workshop into specific requirements for new source evaluations would be very costly. It is suggested that the National Weather Service assist as much as possible by altering, where feasible, its current data acquisition and processing procedures and instrumentation.

In the list of recommendations, Panel A has suggested only those items for which major needs exist, and which would have considerable transfer value from NWS sites to pollutant source locations.

Recommendations which would be incompatible with aircraft operations have been avoided because many of the NWS stations are at airports. The list is therefore restricted to low-level measurements (~ 10 m), or measurements from remote sensors.

Special efforts should be made to obtain more frequent radiosonde data. A series of at least four per day, for periods of approximately 3 to 4 months in various sections of the U.S., would be very helpful. They would be of maximum benefit if the program were conducted on a firm schedule, published well in advance.

The list of recommendations is presented in Tables 5-1, 5-2, and 5-3. The tables detail recommended low-level quantities, low-level measurements desirable at locations relatively free of wakes and runway surfaces, and recommended high-level measurements from remote sensors.

TABLE 5-1
RECOMMENDED LOW-LEVEL MEASUREMENTS AND DERIVED QUANTITIES

<u>Quantity</u>	<u>Type of Change</u>		<u>Priority</u>
	<u>Instrumentation</u>	<u>Data Processing</u>	
$\bar{u}$ and $\bar{\theta}$ at 10 m		Alter data processing to provide mean values over the hour.	1
$\bar{u}$ at 10 m	Improve sensor to provide lower threshold speed		2
$\bar{\theta}$ at 10 m	Improve sensor to provide better damping (to 0.4 but < 0.65)		2
σ_{θ}		Compute hourly standard deviations.	1
σ_v	Same sensor as for $\bar{u}$	Compute hourly standard deviations	As a substitute for σ_{θ} if it should be easier
Total Solar Radiation	Additional equipment required	mean hourly values	1

TABLE 5-2
DESIRABLE LOW-LEVEL MEASUREMENTS

<u>Quantity</u>	<u>Type of Change</u>		<u>Priority</u>
	<u>Instrumentation</u>	<u>Data Processing</u>	
σ_w	New sensors required for vertical wind	Processing to obtain 1-hr standard deviation	2
ΔT 2 m-10 m & $\bar{u}$ at 10 m	New ΔT sensors required for bulk Richardson number	Requisite processing for 1-hr values	2

Note: These data would be useful if they can be obtained at locations relatively free of aircraft wakes, building effects, runway surfaces, etc.

TABLE 5-3
RECOMMENDED HIGH-LEVEL MEASUREMENTS
FROM REMOTE SENSORS

<u>Quantity</u>	<u>Comment</u>	<u>Priority</u>
$\bar{u}$ above 100 m	An elevated wind speed measurement at some standard (agreed-upon) height	1
h_c	The depth of the convective mixing layer, as available from acoustic or other sounders	2
$d\theta/dz$	Measurements of wind shear in the first 2000 meters would be helpful	3

6. ARCHIVING AND RETRIEVAL OF DATA

Most primary data will be collected by an automated system, and will be initially formatted autographically and/or digitally, depending on site instrumentation. Autographic data should be reduced to digital form to eliminate difficulties inherent in their archiving, retrieval, and use. In order that data be available to users, a responsive data archiving and retrieval system is needed.

The following actions are suggested.

- Fix the retrieval and user requirements for data quantities, including both derived and measured quantities. (There is no point, for example, in archiving data which lose their utility beyond the real-time application.)
- Establish the data base access strategy to optimize file design.
- After quantities to be archived are determined, choose a format which accommodates all data, is site-independent, and is compatible with the data base access strategy.
- Preprocess data on-site as completely as possible, but keep enough detail to permit subsequent processing. Retain complete details for periods of special interest.
- Establish quality assurance guidelines for preprocessing and on-site data collection processes. Pre-archival processing could include flagging of suspect data to warn the user.
- Maintain site and instrument descriptions, and documentation of processing techniques for each site as an integral part of the system.

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APPENDIX A

DATA REQUIREMENTS

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1. INTRODUCTION

Panel A was asked to review modeling data requirements, a task which we interpreted as including both current and future modeling needs. We were also asked to consider the representativeness of such data, as well as accuracy, time averaging, period of record, and archiving. Finally, Panel A was expected to recommend changes and additions to National Weather Service (NWS) measurements that could help in providing the data needed by air pollution specialists.

Panel A developed a series of tables listing the key variables in air quality modeling. For this initial review, the problem was treated as though the site in question were flat and uncomplicated, ignoring the possible horizontal variations which could make a single data set unrepresentative, but taking full account of the need for representativeness in the vertical. For each variable or derived quantity, we chose appropriate heights for the measurements, specified appropriate averaging times, and considered the priority of the measurement with respect to one or more applications.

We decided that it would be unproductive to define the required accuracy of the measurements, since it would involve the desired accuracy of the predicted ground-level concentrations, by no means a stationary target. Instead we listed the sensitivity of the dispersion property to the measured variable in two ways, first as the index in a power law (e.g., $\sigma_y \propto \sigma_\theta^1$), and also on a simple relative scale where a value of 1 meant high sensitivity (as concentration to u) and 3, low sensitivity.

The difficult problem of data representativeness was addressed by considering three types of sites in addition to the idealized flat terrain location: (1) rough, complex terrain, (2) a land-water interface, and (3) an urban-rural boundary area.

2. SPECIFIC VARIABLES REQUIRED FOR PLUME RISE AND DISPERSION MODELING

Tables 1 and 2 list the variables and derived parameters important in modeling plume rise and dispersion. From the basic quantities, other hybrid parameters can be developed or estimated. The tables are supplemented by descriptions and comments, where necessary.

In the columns designated as sensitivity, Exp denotes the approximate quantitative effect of the variable on the application in question. An Exp entry of -1, for example, means that concentrations would be inversely proportional to this variable. An entry of 1/3 indicates that the concentrations or plume rise would vary as the 1/3 power of the variable. The second entry, Rel, is a qualitative estimate of the effect of the variable on the modeling results, measured as (1) important, (2) moderate, or (3) minor. The entry designated as Priority means the quantity is (1) essential, (2) desirable, or (3) helpful in modeling atmospheric dispersion.

2.1 Quantities Measured at Different Heights or Height Intervals

Table 1 lists variables that change significantly with height and which must at least be estimated at varying elevations above ground. Each of these variables is discussed in the following sections.

$\bar{u}$:

The mean wind speed, $\bar{u}$, affects diffusion in two important ways: plume rise and longitudinal dilution. The sensitivity of plume rise to $\bar{u}$ varies with stability. In stable conditions it depends approximately on $\bar{u}^{-1/3}$, while in neutral conditions it may vary as $\bar{u}^{-2}$; for unstable conditions the sensitivity is intermediate. For all conditions, the dependence of concentration on longitudinal dilution is simply $\bar{u}^{-1}$. In addition, a mean wind speed is needed for the bulk Richardson number, a highly desirable parameter for

TABLE 1
QUANTITIES TO BE MEASURED AT DIFFERENT HEIGHTS

Variable	Height of Measurement	Sampling Duration	Sensitivity Exp. Rel.	Application	Priority	Comments
$\bar{u}$	10 m & source height	1 hr	-1	Plume dilution	1	Should be measured at least 60 times/minute.
$\bar{1/u}$	Source height to effective plume height	1 hr	1/3 to 3	Plume rise	1	-
$\sigma(1/u)^*$	Source height	1 hr	*	Plume rise variability	2	Uncertain *Using 1-minute averages of u.
$\bar{\sigma}$	Source height	1 hr	-	Plume placement	1*	*Assuming specific location of concentrations is needed.
$d\sigma/dz$	Through plume depth* 1 hr	1 hr	-	Dispersion	2	*When wind shear is significant $d\sigma/dz$ contributes to σ_y .
σ_0	10 m	1 hr	-1	Dispersion	1	To obtain total variance over the hour.
σ_y	Source height	1 hr	-1	-	2	To obtain total variance over the hour.
	10 m	1 hr	-1	Dispersion Flow characterization	1	
ΔT	Source height	1 hr	-1	Dispersion	2*	*Can be estimated from other data.
	2 m to 10 m	1 hr	-1/2 to +1/2	Dispersion	1	-
ΔT	Source height to effective plume height	3 hr	-1/3	Plume rise	2	*Could use representative radiosonde data.
Pr	Should represent 1-hour conditions from near surface to terrain top or above near obstacles.					
T_d	Source height to effective plume height	3 hr	-1*	Cooling tower plume persistence	1*	*Assuming cooling tower plume visibility is important.
T	2 m	1 hr	-1/3	Plume rise	1	-
σ	10 m & source height	1 hr			3	Generally significant only in complex terrain.

TABLE 2

QUANTITIES TO BE EVALUATED NEAR THE GROUND OR AT DESIGNATED ELEVATIONS

Variable	Height of Measurement	Sensitivity Exp. Rel.	Application	Priority	Comments
u_z	Surface	-4/3 1	Plume rise neutral case only	1	-
u_z		± 1 2	σ_z diffusion near ground	1	-
z_0	Surface	1/6 3	For estimation of u_z , L^+	1	*Using estimated relationships
z_0		1/6 3	Wind profile at low ele- vations	1	-
L	Surface	-1/2 to $\pm 1/2$ 1	Diffusion near ground, σ_z , and stability charac- terization	1	-
R_{10}	Surface	-1/2 to $\pm 1/2$ 1	For estimation of L^+ characterization of stability	1	*Using established relationships
H_f	Surface	-1 2 1/3 1	For estimation of L (stability) For estimation of w_e	1	-
w_e	Surface	-2* 1	σ_z and σ_y in convective conditions	1	Effect on concentration through σ_y and σ_z
h_c	Layer	0 to ∞ 1	Plume rise	1	
h_c	Layer	-1/2 to 0 2	Dispersion*	1	*Prior to plume intersection with lid
h_c	Layer	-1 1	Dispersion*	1	*After plume has intersected lid
h_c	Layer	1/3 1	Estimation of w^*	1	
h_m	Layer	-1* 1*	Containment of low sources at night, entrainment of ele- vated plume	1	*After plume has intersected lid

Note: Sampling duration is 1 hour for all variables.

characterizing the surface layer and vertical dispersion near the ground. In this application, the vertical dispersion at a given distance can depend on $\bar{u}^{-1}$ in very unstable conditions.

Adequate wind speed measurements for all these purposes can be made at a single location free of interference from structures. For bulk Richardson number determination, a 10 m measurement height is preferred. For plume rise and dilution, the preferred height is the final plume height. However, for normal accuracy this is not necessary.

There is little wind shear above 50 m in unstable conditions, so $\bar{u}$ at source height or the top of a tower is adequate. In neutral conditions, extrapolation of the logarithmic profile law from these heights is adequate, provided that the roughness length of the surface near the source is reasonably estimated (this only requires a description of the ground cover in the area). In stable conditions, wind shear can be large above this measurement height, but plume rise depends only on $\bar{u}^{-1/3}$. Except for elevated structures or terrain, high rising plumes in these conditions rarely affect the ground until breakup fumigation occurs; the resultant ground concentration then depends on the inverse of the total height of the plume, but is just as sensitive to other factors less well known. Therefore, $\bar{u}$ at source or tower height is adequate for most site and accuracy requirements.

For low level sources, large wind shear near the ground needs to be accounted for in modeling. But $\bar{u}$ as a function of z can be calculated from $\bar{u}$ at a single height, such as 10 m, in combination with either the bulk Richardson number or some other determinant of L , the Monin-Obukhov length.

For hourly wind speed averages, about 60 samples of the velocity per hour are needed. It is preferable to average $(1/\bar{u})$ rather than inverting $(\bar{u})$ for plume rise and dilution.

In low wind speed convective conditions, fluctuations in plume rise due to variations in $\bar{u}$ can significantly increase vertical dispersion. One-minute averages adequately monitor these fluctuations, and the variance $\sigma(1/\bar{u})$ of a hour-long series of these 1-minute averages would be the best measure for estimating the variance in plume rise. For low wind speed convective conditions

fluctuations in $\bar{u}$ affect plume rise and transport significantly and thus are critical.

$\bar{\theta}$:

The 1-hour average horizontal wind direction, $\bar{\theta}$, has two important uses: the placement of the plume in the x-y plane, and in the determination of the direction shear in the atmospheric layer in which the plume is dispersing.

For the placement of the plume, $\bar{\theta}$ measured near the source at a height of 10 m and at the top of the meteorological tower should be sufficient for modest source heights and close distances (<10 km) in cases other than complex terrain. In complex terrain, θ measurements at additional sites may be required. A special case is the direction of travel of elevated plumes as related to underlying or intercepting high terrain. For plume travel of distances greater than 100 km, a wind field derived from standard NWS measurements of wind profiles may be required.

The importance of wind direction shear with regard to crosswind dispersion from tall stacks is primarily limited to downwind distances of 10 km or more. Also, complex terrain often exhibits very drastic shears in shallow layers close to the ground and measurements at additional sites may be required.

$\sigma_{\theta}, \sigma_{\phi}, (\sigma_v, \sigma_w)$:

Standard deviations of wind fluctuations are needed (1) to directly characterize the dispersion parameters (σ_y and σ_z) and (2) in place of u_* and H_F to characterize the boundary layer structure as affected by roughness and thermal stratification. The grade (1) sensitivity reflects the expected linear proportionality between σ_y or σ_z and σ_{θ} or σ_{ϕ} .

Modeling in the context of chemical transformation should refer strictly to instantaneous concentrations and hence to the instantaneous dimensions of the plume. For a power plant plume, these dimensions are first determined (i.e., at short range) by the

buoyancy-induced entrainment. Only with increasing distance are the appropriate σ values affected by ambient turbulence. Then, however, they obviously must be less than the total values derived by adding the buoyancy-induced entrainment σ^2 to the σ^2 evaluated from 1-hour averages of σ_θ and σ_ϕ (e.g., instantaneous σ_z^2 is always somewhere between σ_{zb}^2 and $\sigma_{zb}^2 + \sigma_{zw}^2$, where σ_{zb} refers to the buoyancy-induced entrainment and σ_{zw} refers to the 1-hour average of σ_ϕ).

It was agreed that the priority should be lower at the stack or source height than at 10 m for both parameters. Given σ_w at the low level, a useful extrapolation may be made to higher levels in some cases, using the known dependence of this variable on z/L and z/h_c . Then for estimates of short-range dispersion of a power plant plume, the buoyancy-induced entrainment is more important than ambient turbulence.

It was also recognized that, with sampling time specified, requirements for specifying suitable reading intervals and smoothing time and time-constant remained to be specified to ensure adequate derivation of the total variance within some reasonable limit. But these aspects were deferred for consideration by Panel C.

$\Delta T/\Delta z$:

The temperature gradient, $\Delta T/\Delta Z$, is needed for two purposes: plume rise in stable conditions and characterization of the surface layer. Plume rise is not very sensitive to this quantity (being proportional to $(\Delta T/\Delta Z)^{-1/3}$), but an estimate is needed over the layer of plume rise. The best $\Delta T/\Delta Z$ for this purpose is from the top of the stack to the top of the plume. Elevated plumes in stable conditions do not usually reach the ground until inversion breakup fumigation occurs, and there is probably much more uncertainty about σ_y than about plume height. In this case, a determination of $\Delta T/\Delta Z$ from routine NWS radiosonde soundings will be adequate for most sites. The most obvious exception is the source in a deep valley; since σ_y is constrained by the valley walls, inversion breakup fumigation may be of critical interest, but temperature soundings

outside the valley are irrelevant. For this purpose, a study of the vertical temperature structure at the specific site may be necessary.

The temperature gradient near the ground is needed for determining the bulk Richardson number, in turn a convenient determinant of L , which very effectively characterizes vertical diffusion near the ground. In addition, $\Delta T/\Delta Z$ below 30 m correlates well with H_p in unstable conditions. In these conditions, concentrations can vary with $|\Delta T/\Delta Z|^{-1.2}$. The recommended height interval for these purposes is ΔT between 2 m and 10 m. When there is a tower at the site, ΔT between the tower top and 10 m should also be provided as a supplementary stability measure. One-hour averaging times are convenient.

Fr:

The Froude number, Fr , is a measure of the importance of density stratification on flow in complex terrain. It has been shown to be valuable in fluid modeling studies during stable conditions where it helps specify the flow pattern over, around, and downwind of a hill as a function of hill size, flow velocity, and density (temperature) gradients. In the atmosphere, velocity and density gradients are not often linear in complex terrain. This requires that care be taken in evaluating (and therefore detecting) multiple layering of the atmosphere. When multi-layering occurs, the appropriate Froude number will depend on layer properties at release height, effective plume height, and at heights in excess of the terrain elevation.

2.2 Quantities Measured at the Ground at Designated Intervals

Table 2 lists a set of important measurements or derived variables which have little relation to height. It is sufficient to evaluate these quantities at the surface or at a designated elevation. Each is discussed in the following sections.

u_* :

The friction velocity, u_* , is needed to predict plume rise in neutral conditions, and it also provides one way to estimate the Monin-Obukhov scaling length. For plume rise, it is the most convenient means for estimating ϵ at plume height during neutral conditions, and also characterizes the magnitude of vertical velocities that cause an elevated plume to reach the ground. Plume rise depends approximately on $u_*^{-4/3}$ (Briggs 1975). For this purpose, it is usually adequate to apply the logarithmic wind profile law for neutral conditions, $u_* = 0.4\bar{u}_t / \ln(z_t/z_0)$, provided that the surface roughness length, z_0 can be reasonably estimated, where z_t is the reference height of the upper wind speed measurement, say at stack height. A factor of 2 accuracy is acceptable for the z_0 estimate; this can be achieved by an experienced observer or obtained from a careful description of the ground cover surrounding the site. The cover at a radial distance of roughly 10 to 40 z_t is most relevant. The wind speed used should be that at the top of a meteorological tower, $\bar{u}$, since it is less influenced by the immediate surrounding surface than a lower measurement.

If the Monin-Obukhov length, L , is not determined using the bulk Richardson number, it is usually determined from u_* and a heat flux measurement, that is, from $L = -u_*^3 c_p T / (k g H_F)$. From its definition, L is proportional to u_*^3 , so L is quite sensitive to the surface friction velocity. The vertical dispersion from a source near the ground is highly correlated with L , but at most it depends on $|L|$ to the plus or minus 1/2 power. From this, we would say that σ_z is only fairly sensitive to u_* . For this purpose, L may be adequately estimated from $\bar{u}$ at 10 m using known surface layer profile relationships. This latter analysis may require iterative techniques since $u_*/\bar{u}$ is a function of z_0/L and z/L .

H_F , L and w_* :

Surface heat flux, H_F , is a basic parameter characterizing the boundary layer structure in the surface layer in conjunction with u_*

through the Monin-Obukhov length scale, L . It is important over the rest of the convective boundary layer in conjunction with h_c through the convective velocity, w_* .

Turbulence intensities and dispersion rates are well correlated with L and w_* , though to an extent that is not true of H_F itself; in convective conditions velocity variances and σ_z behave as $H_F^{1/3}$ and $H_F^{1/2}$, respectively, at most. In very stable conditions, field studies indicate that with passive surface releases, the sensitivity of σ_z becomes greater than $|H_F|^{1/2}$. One might have expected H_F to be an important determining factor for h_m at night but apparently this factor is overshadowed by u_* .

Considerable spatial variation of H_F and the dependent parameter L are to be expected as a result of transitions in surface characteristics (especially albedo and wetness). For this reason, a direct measurement, which is difficult to make, at a single point is of dubious value; some of the indirect measures, such as solar insolation, might actually be more broadly representative. There are several variables that can be used as indicators of or contributors to heat flux. These include net radiation, sky radiation, sky cover, solar elevation, state of ground, and evapotranspiration. None of these in itself can be substituted for the heat flux. Only sky cover and solar elevation have been used systematically (with other variables) to replace the heat flux factor for estimating dispersion. The roles of the other variables for estimating the heat flux warrant further study. H_F can also be determined from variances of turbulence quantities that are directly influenced by H_F , such as σ_T or, in convective conditions, σ_w .

ϵ :

The eddy dissipation rate, ϵ , characterizes the high frequency (small eddy size) part of velocity spectra, and in dispersion models is used chiefly as a factor influencing plume rise in neutral and unstable conditions. Plume rise depends on $\epsilon^{-2/5}$, approximately, so estimation of ϵ within $\pm 50\%$ is usually adequate. It is believed that this accuracy can be obtained from knowledge of surface parameters,

especially u_* and H_F , for the conditions of interest. There is a need for further research on the dependence of ϵ on height and on its variation within large convective structures (it is known to be much larger in thermals than in downdrafts, and some models require separate values).

h_c :

The importance of the convective mixing depth, h_c , is that it limits the vertical dimension of the pollutant cloud, and in so doing reduces the dilution of concentration with downwind distance. It also may inhibit or stop plume rise so that higher maximum downwind concentrations result from an elevated plume. Used with a measure of surface heat flux, it characterizes the whole convective layer, including turbulent velocities. h_c has a definite diurnal variation, increasing in depth after daybreak, reaching a maximum in the early afternoon. The mixing layer typically decays at dusk to be replaced by the characteristic nighttime, ground based radiation inversion layer except during cloudy and windy conditions.

h_m :

The mechanical mixing layer, h_m , is generally a nocturnal feature, driven by strong wind shear near the ground. Near-surface or small stack emissions may be trapped in the layer with no vertical growth beyond h_m but can at the same time exhibit considerable lateral meandering. The net downwind concentration effect on low-level sources generally results in higher downwind concentrations than would be experienced in the daytime convective mixed layer. Near an urban area, h_m may sometimes merge with h_c over the city because of the urban heat island effect. This can possibly result in a nighttime rural elevated plume being prevented from reaching the rural surface, and, upon being transported towards an urban area, essentially being fumigated to the heat island ground surface. After leaving the urban area it may be lifted again above the rural h_m . In complex terrain h_m can deepen as a result of the downslope air

drainage within valleys. Furthermore, side valleys, canyons, and compensating flows can generate overriding or undercutting outflows that may cause plumes at different elevations to move in different directions. No model relating h_m to other more easily measured variables has gained acceptance, but it seems likely that h_m is most strongly correlated with u_* .

σ_T :

The standard deviation of the near surface (10 m) temperature is of interest for the validation of second order closure models. It can be used for an estimate of surface heat flux, primarily under unstable conditions. The low frequency contribution to the variance represented by the gradual trend in temperature as the hour progresses should be eliminated.

3. GENERAL METEOROLOGICAL MEASUREMENTS

Other sections of the report deal with variables specifically required for the modeling of plume rise and dispersion. For certain applications, such as long-range transport or the establishment of relations with more general meteorological patterns, additional data are required. These quantities are listed in Table 3 and are generally self-explanatory. Specification of the horizontal wind and temperature fields clearly is related to representativeness of the data (discussed in more detail in the next section), and the geostrophic wind may be a convenient substitute for upper wind measurements, especially if long-range transport is involved.

Solar radiation and net radiation are included because they may already be included in the measurements made at some standard observation stations, and because they can serve as an indicator of heat flux. The state of the ground also exerts important control on the heat flux.

TABLE 3
GENERAL METEOROLOGICAL MEASUREMENTS

Variable	Height of Measurement	Sampling Duration	Sensitivity Exp. Rel.	Application	Priority	Comments
Horiz. + Wind Field	Source height	1 hr	0 to ∞	Transport	1*	*If position of plume is important. +Given by $\bar{\sigma}$ & $\bar{u}$ unless area is complex. +Given by $\bar{T}$ unless area is complex.
Horiz. + Temp. Field	Source height	1 hr	Site dependent		3	
Geostrophic Wind		3 hr	NA		3	Priority could be higher for long-range transport
Solar Radia- tion	Surface	1 hr	+1	Dispersion	2	Useful for heat flux and for photochemical effects
Net Radia- tion	This requirement is complex and can be provided in different ways--see text.					
State of Ground	Surface	3 hr	Unspecified	Dispersion	3	

4. DATA REPRESENTATIVENESS

Transport and diffusion models can simulate atmospheric processes accurately only if the input data faithfully represents the area and volume in which the processes operate. While the dangers of inadequate input are clear, nonrepresentative data are too easily tolerated.

We recommend that the terms "representativeness" and "representative siting" be given practical, mathematical definitions. These definitions will permit comparisons between data collected at different sites. Research is required to develop acceptable threshold values for these differences. The threshold should be greater than the "functional precision" of the instrument (Hoehne 1977). The functional precision is the root mean square of differences between two identical sensors mounted without influencing one another, at the same height and as close to each other as practical (within 10 m). The difference between the functional precision of identical types and different types describes the difference in instrument performance.

4.1 Types of Representativeness

Primitive representativeness (R_p) is equivalent to correlation of time synchronous data. The flow field might be called frozen where every point changes in the manner point A changes at the time point A changes. Hence, another point B would have a data set identical to point A. For wind data:

$$\bar{u}_b = \bar{u}_a$$

$$\bar{\theta}_b = \bar{\theta}_a$$

for any sampling time, method of averaging time, or location.

Climatological representativeness (R_c) is based on the shape of the distribution over a long period of time. This type of representativeness may be dependent on time over short periods, but

the distribution of average values at point B is represented by the distribution measured at point A.

For this type of representativeness

$$\sum \frac{(\bar{u}_b)}{N} = \sum \frac{(\bar{u}_a)}{N}$$

$$\sigma(\bar{u}_b) = \sigma(\bar{u}_a)$$

$$S_K(\bar{u}_b) = S_K(\bar{u}_a)$$

$$K(\bar{u}_b) = K(\bar{u}_a)$$

where

N = number of sampling intervals within the period of record

S_K = skewness

K = kurtosis

Spatial representativeness (R_s) can be considered a special case of primitive representativeness. Measurements at point A should be representative of the spatial average over some horizontal area on the order of 1 to 10 km. This is usually the representativeness referred to when characterizing upward heat flux with a minimum of instrumentation over a surface area of great variability.

4.2 Flat Terrain

Panel A assumed that primitive representativeness is valid to distances of approximately 20 km within flat terrain. In practice, certain variables may not meet this assumption. Upward heat flux and net radiation are typically so sensitive to surface characteristics that spatial representativeness may be very difficult to attain with a single measurement site. It is also possible that measurements of bulk Richardson number may require more than one site.

4.3 Complex Terrain

Primitive representativeness is extremely limited in complex terrain. Hence, the meteorological monitoring should be determined on a case-by-case basis. For instance, the placement of an elevated plume, horizontally and vertically, requires detailed knowledge of the flow field. Even then, time lapse photographs of continuous smoke releases may still be required to define the trajectory*. At present, mathematical modeling of flow fields is inadequate for the definition of plume trajectories. The specification of the profiles of turbulence intensities would also require measurements along the plume trajectory since the extrapolation of such quantities from near-surface measurements is unreliable. In deep valley situations, the temperature lapse rate over the depth of the buoyant plume rise is needed for proper modeling of inversion breakup fumigation.

In summary, because of current inability to reliably characterize wind flow and turbulence structure in complex terrain, these variables must be measured. The degree of specification is partly model-sensitive. However, even if a model is incapable of handling complex flow (such as curved trajectories), the knowledge of such trajectories may be important if the terrain height is greater or less than the effective source height. The wind flow structure is further complicated by (1) upslope and downslope winds, (2) wind channeling effects, (3) lee wave phenomena (density stratification), and (4) divergence.

4.4 Urban/Rural Interaction

Plumes from sources near urban areas may have both urban and rural characteristics. Although "near" has not been defined formally, sources within 3 km downwind of an urban area seem to be influenced, depending on the size of the city. For these cases, meteorological

*Available models cannot consistently and accurately duplicate real flow fields, thus estimating maximum short-term (1-hour) concentrations due to elevated plumes remains inadequate.

measurements should be taken at two locations, urban and rural. The measurements will help model dispersion when the source is upwind or downwind of the city. The special circulations that can be induced by the urban heat island during low wind conditions should also be considered. The priority of the variables listed in Tables 1, 2, and 3 are the same.

4.5 Land/Water Interface

The unique meteorological features of a shoreline require special on-site measurement considerations. There are three main effects of the shoreline environment on the dispersion characteristics of the atmosphere: (1) mesoscale recirculation due to sea (or lake) and land breezes (Lyons 1973), (2) changes in atmospheric stability caused by the development of internal boundary layers due to changes in roughness and heating (Raynor et al. 1979, SethuRaman 1980), and (3) a combination of these two.

For example, a stable stratified air mass over water can become unstable over land during daytime conditions and onshore flow. This will cause releases from a coastal source to behave like a stable plume, fumigating further downwind. Because internal boundary layers with steep slopes can develop in the leading edge, such fumigation could occur near the boundary depending on the effective source height. For these reasons, a model that uses meteorological measurements made at one location at a coastal site will not be able to predict the downwind ground-level concentrations due to the changes in stability.

It is recommended that the measurements for flat terrain be made at a minimum of two locations, one at the shore representative of the over water conditions for onshore flow, and the other about 1 km inland where the conditions are representative of the air mass inside the internal boundary layer. For the site inland, near surface measurements up to a height of 10 m will suffice. For sites where chemical transformations are significant, humidity measurements will be important at least at one level. Additional monitoring is necessary over water for diffusion during land-water-land cases, such

as near lakes and rivers. Where the shoreline terrain is more complex, including bluffs, measurements at additional locations will be necessary and should be determined on a site-specific basis.

4.6 Length of Record

At least one year of synchronous data, collected at two sites, is necessary to assess spatial representativeness, assuming the data record is reasonably complete. However, to establish whether a year of data is typical or climatologically representative, more than one year of data is required. It is therefore recommended that 2 or 3 years of data be used to determine climatological representativeness, with the possibility of re-analysis as new data become available.

5. RECOMMENDATIONS FOR THE OFFICE OF THE FEDERAL COORDINATOR FOR METEOROLOGY

Translating the recommendations of this workshop into specific requirements for new source evaluations would be very costly. It is suggested that the National Weather Service assist as much as possible by altering, where feasible, its current data acquisition and processing procedures and instrumentation.

In the list of recommendations, Panel A has suggested only those items for which major needs exist, and which would have considerable transfer value from NWS sites to pollutant source locations.

Recommendations which would be incompatible with aircraft operations have been avoided because many of the NWS stations are at airports. The list is therefore restricted to low-level measurements (~ 10 m), or measurements from remote sensors.

Special efforts should be made to obtain more frequent radiosonde data. A series of at least four per day, for periods of approximately 3 to 4 months in various sections of the U.S., would be very helpful. They would be of maximum benefit if the program were conducted on a firm schedule, published well in advance.

The list of recommendations is presented in Tables 4, 5, and 6. The tables detail recommended low-level quantities, low-level measurements desirable at locations relatively free of wakes and runway surfaces, and recommended high-level measurements from remote sensors.

TABLE 4
RECOMMENDED LOW-LEVEL MEASUREMENTS AND DERIVED QUANTITIES

<u>Quantity</u>	<u>Type of Change</u>		<u>Priority</u>
	<u>Instrumentation</u>	<u>Data Processing</u>	
$\bar{u}$ and $\bar{\theta}$ at 10 m		Alter data processing to provide mean values over the hour.	1
$\bar{u}$ at 10 m	Improve sensor to provide lower threshold speed		2
$\bar{\theta}$ at 10 m	Improve sensor to provide better damping (to 0.4 but < 0.65)		2
σ_{θ}		Compute hourly standard deviations.	1
σ_v	Same sensor as for $\bar{u}$	Compute hourly standard deviations	As a substitute for σ_{θ} if it should be easier
Total Solar Radiation	Additional equipment required	mean hourly values	1

TABLE 5
DESIRABLE LOW-LEVEL MEASUREMENTS

Quantity	Type of Change		Priority
	Instrumentation	Data Processing	
σ_w	New sensors required for vertical wind	Processing to obtain 1-hr standard deviation	2
ΔT 2 m-10 m & $\bar{u}$ at 10 m	New ΔT sensors required for bulk Richardson number	Requisite processing for 1-hr values	2

Note: These data would be useful if they can be obtained at locations relatively free of aircraft wakes, building effects, runway surfaces, etc.

TABLE 6
RECOMMENDED HIGH-LEVEL MEASUREMENTS
FROM REMOTE SENSORS

<u>Quantity</u>	<u>Comment</u>	<u>Priority</u>
$\bar{u}$ above 100 m	An elevated wind speed measurement at some standard (agreed-upon) height	1
h_c	The depth of the convective mixing layer, as available from acoustic or other sounders	2
$d\theta/dz$	Measurements of wind shear in the first 2,000 m would be helpful	3

6. ARCHIVING AND RETRIEVAL OF DATA

Most primary data will be collected by an automated system, and will be initially formatted autographically and/or digitally, depending on site instrumentation. Autographic data should be reduced to digital form to eliminate difficulties inherent in their archiving, retrieval, and use. In order that data be available to users, a responsive data archiving and retrieval system is needed.

The following actions are suggested.

- Fix the retrieval and user requirements for data quantities, including both derived and measured quantities. (There is no point, for example, in archiving data which lose their utility beyond the real-time application.)
- Establish the data base access strategy to optimize file design.
- After quantities to be archived are determined, choose a format which accommodates all data, is site-independent, and is compatible with the data base access strategy.
- Preprocess data on-site as completely as possible, but keep enough detail to permit subsequent processing. Retain complete details for periods of special interest.
- Establish quality assurance guidelines for preprocessing and on-site data collection processes. Pre-archival processing could include flagging of suspect data to warn the user.
- Maintain site and instrument descriptions, and documentation of processing techniques for each site as an integral part of the system.

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APPENDIX B

MEASUREMENT TECHNIQUES - DERIVED VARIABLES

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1. INTRODUCTION

The objective of Panel B was to summarize the derivations and characteristics of dispersion-related variables derived from basic meteorological measurements. Characterization of these variables included assessments of accuracy, use, and influence on the results of diffusion calculations.

Section 2 is a condensed summary of the panel's conclusions in the form of individual exhibits or tables which focus on the individual parameters. A more detailed presentation of Panel B's discussions and recommendations follows in Section 3.

2. PRESENTATION OF PANEL CONSENSUS

Evaluation of dispersion-related variables derived from basic measurements followed a flexible format. This format included consideration of:

- possible modeling use,
- basic measurements required,
- accuracy of the derived variable,
- influence of the derived variable on diffusion calculations,
- method of deriving variable, and
- recommendations.

This format has been used as a device for presenting a summary of the panel's conclusions. Eight exhibits cover wind field standard deviations, roughness length scale, Richardson number, friction velocity, convective velocity scale, Monin-Obukhov length scale, heat flux, and Pasquill-Gifford dispersion classes.

EXHIBIT 2.1: WIND SIGMAS ($\sigma_u, \sigma_v, \sigma_w, \sigma_\theta, \sigma_\phi$)

	<u>Ground Level Release</u>	<u>Elevated Release</u>
<u>Possible Modeling Use:</u>	K-Theory for σ_z Lagrangian Similarity Theory for σ_z , Statistical Theory for σ_y (see Pasquill 1975)	Plume Rise ¹ and Statistical Theory
<u>Basic Measurement:</u>	Wind speed and direction	
Height:	10 m	Plume Centerline ²
Location:	Representative Surface (not near terrain)	
Averaging Time for basic measurement:	1-5 sec	1-5 sec
Response Duration (Time Constant):	1 sec	1 sec
Sampling Duration ³ :	3 minutes or greater depending on travel time to receptor	
Accuracy:	u, v, w 0.2 m/sec + 5% (max) θ, ϕ 30	- -
Accuracy of Derived Variable ⁴ :	5-10%	7-30%
<u>Influence of Derived Variable on Diffusion Calculation:</u>		

Through σ_y and σ_z (see Table 2 in Pasquill 1975).

Method of Deriving Variable:

Statistical Analyses of Measurement Records for each of the respective components.

Recommendations:

#1. NWS should use a 1-hour sampling duration for wind direction and wind speed. They should report σ_θ based on the same 1-hour sampling duration.

#2. The variables σ_θ and σ_ϕ should be calculated directly, rather than by using a range estimator.

#3. It is recommended that a sampling duration shorter than one hour for both means and standard deviations of wind components be considered when modifications of NWS recording and archiving procedures are planned. The principal use of short-term values (e.g., 3-15 min) is for models designed to assess trajectories and impacts of short-term (often accidental) pollutant releases. Thus, the archive recordings could be recycled every one to four weeks to avoid expensive modifications in long-term archival data sets.

#4. For industrial or other sites likely to experience noncontinuous releases of pollutants, statistics based on a 3-minute sampling duration for σ_θ (at least) should also be permanently archived. This will allow σ 's for this short sampling duration to be combined and appropriately matched with release duration in modeling time-integrated concentration fields.

Footnotes

¹ σ_u is usable for modification of plume rise estimates for puff releases.

²Measurements could be made at release height if they were the only feasible alternative.

³Three minutes based on historical estimates of σ_y from original Porton experiments and other experiments designed to utilize lateral P-G dispersion rates. Idaho experiments on diffusion under low wind speed conditions have also illustrated the utility of this approach (Sagendorf and Dickson 1974).

⁴Specific cases will vary depending on degree of long wave convective contribution to the turbulence measurement that can be identified as a separate component by trend analysis.

EXHIBIT 2.2: ROUGHNESS LENGTH (z_0)

Ground Level
Release

Possible Modeling
Use:

Lagrangian similarity theory

Basic Measurement

Wind speed

Height: Minimum of three heights
between 2-20 m

Location: Representative of the surface

Averaging time: 30 sec

Instrument
response duration: 10 sec

Sampling duration: 1 hour

Accuracy: 5%

Accuracy of the derived variable: within a factor of 2

Use of the derived variable
in diffusion calculations:

(1) In Lagrangian similarity relations for plume height and ground-level concentration.

(2) In the similarity relations for u_* , H_F , L , etc. and in conversion between P-G stability classes and Ri_B or L .

Influence of derived variable on the
accuracy of diffusion calculations:

Since only $\log z_0$ is involved in various similarity relations, diffusion calculations are not very sensitive to z_0 and its determination within a factor of 2 may be adequate.

Method of deriving the parameter:

(1) For neutral stability, by fitting the logarithmic wind profile law

$$\bar{u} = \frac{u_*}{k} \ln \frac{z}{z_0}$$

to the measurements of u versus z .

(2) An alternative method is to measure the average height (h_0) and area density of predominant roughness elements and then use an appropriate empirical relation for determining z_0 . This may be preferred for tall roughness as in an urban setting.

Recommendations:

- (1) For determining z_0 from the mean wind profile measurements, anemometers should be placed above the tops of the roughness elements.
- (2) z_0 should be determined separately for different wind directions.

EXHIBIT 2.3: RICHARDSON NUMBER (Ri)

	<u>Ground Level Release</u>	<u>Elevated Release</u>
<u>Possible Modeling Use:</u>	Lagrangian similarity K-theory statistical	plume rise plus statistical K-theory
<u>Basic Measurements:</u>	(1) Ri_f - tower obs. of $u'w'$ & $w'T'$ (2) Ri_Δ - tower obs. of $u\Delta T$ at two levels (3) Ri_B - tower obs. of $u\Delta T$ at h, and T near surface.	(1) for Ri'_B (local): T at two levels and u in between from tall tower, aircraft, or PBL model (2) for Ri_B (SBL) tower obs of $u\Delta T$ at h and T near surface.

Time constant etc: that appropriate for fluctuating or mean quantities
- see Exhibit 2.6 for L, Monin-Obukhov length.

Accuracy of derived variable: derivable from errors in fluctuating or
mean quantities.

Influence on
diffusion: to obtain σ_y and σ_z ; K;
or P-G class

Method of deriving
variable

in order of decreasing
theoretical strength, but
increasing practicality;

(1) in stable PBL case
with low level jet;

Ri'_B (local)
(2) Convective SBL:

Ri_B (SBL)

$$(1) Ri_f = \frac{-g}{T} \frac{\overline{w'T'}}{\overline{u'w'} \partial u / \partial z}$$

$$(2) Ri_\Delta = \frac{g}{T} \Delta z \frac{\Delta \theta}{(\Delta u)^2}$$

$$(3) Ri_B = \frac{z_{10}}{T} \frac{\theta(z_{10}) - \theta(z_2)}{(u(z_{10}))^2}$$

Recommendations:

- (1) The SBL value of the bulk Ri should be used with surface releases.
- (2) The local PBL value of the bulk Ri should be used with elevated releases during stable conditions with low-level jets (LLJ's).

- (3) The SBL value of the bulk Ri should be used to estimate PBL mixing during convective SBL conditions.
- (4) To obtain SBL bulk Ri values, the NWS should measure ΔT between 2 m and 10 m.

EXHIBIT 2.4: FRICTION VELOCITY (u_*)

<u>Possible Modeling Use:</u>	Modeling releases within the surface layer defined by $z = L $. u_* is input for Lagrangian similarity theory or K-theory.
<u>Basic Measurement:</u>	u_* obtained from $\bar{u}$ (10 m) with a drag coefficient from a detailed field experiment; $u_* = C_D \bar{u}$ (10 m)
<u>Influence of derived variable on dispersion calculation:</u>	$c \propto 1/u_*$ (surface releases) $\frac{dc}{du_*} \propto \frac{1}{u_*^2}$; sensitive when u_* is small $c \propto u_*^2$ (fugitive emissions from saltation) $\frac{dc}{du_*} \propto u_*$; sensitive when u_* is large.
<u>Method of Deriving Variable:</u>	$u_*^2 = \tau/\rho = -\overline{u'w'}$ (constant flux layer) (1) Eddy correlation to determine $-\overline{u'w'}$ Location: 10 m, Reading interval: 1/5 Sec, Sampling time: 60 min; Accuracy: 20% (2) Drag plate measurement of τ (shear stress) Location: surface, Reading interval: depends on instrument sensitivity. Sampling time: 60 min; Accuracy: 40% (3) Profile measurements of temperature and velocity Location: 2 or 3 levels below 10 m Reading interval: 1 min, Sampling time: 60 min Accuracy: less than direct methods
<u>Recommendations:</u>	Profile measurements of temperature and velocity constitute the most practical method to derive u_* for dispersion calculations.

EXHIBIT 2.5: CONVECTIVE VELOCITY SCALE w_*

<u>Possible Modeling Use:</u>	Used primarily in modeling pollutant releases into the mixed layer from sources above 0.1 h _c (see Deardorff and Willis 1975, Venkatram 1980)
<u>Basic Measurement:</u>	(1) Surrogate methods are well suited for this application; e.g., tower 10 m high equipped with platinum wire thermometer to measure σ_T, which can be used to compute Q_0. (2) $w_* = F(t) Q_0$; w_* can be estimated from solar radiation or mixed layer height (see Venkatram 1978).
<u>Influence of derived variable on dispersion calculation:</u>	$c \propto 1/w_*$ (approximately) Concentration is sensitive to w_* when w_* is small.
<u>Method of deriving variable:</u>	$w_* = \left(\frac{g}{T} Q_0 h_c \right)^{1/3}$, $Q_0 = \overline{w'T'}_0$ (1) Eddy correlation measurement of $w'T'$ Location: 10 m; Reading interval: 1/5 sec Sampling time: 60 min; Accuracy: 15%(?) (2) Profile measurements of temperature and velocity Location: 2 to 3 levels below 10 m, Reading interval: 1 min. Sampling time: 60 min; Accuracy: 20% (?) (3) Surrogate methods of measuring $\overline{w'T'}$ (See Businger 1973 and Wyngaard et al. 1978).
<u>Recommendations:</u>	Surrogate methods to measure Q_0 are well suited for most applications. Acceptable estimates of w_* can be derived from this Q_0 . Optical and acoustic remote sensing techniques to measure C_T^2 and C_n^2 are suitable for deriving routine estimates of w_* . If nothing else is available, incoming solar radiation or net radiation can be used to derive acceptable estimates of w_* .

EXHIBIT 2.6: MONIN-OBUKHOV LENGTH (L)

	<u>Ground Level Release</u>	<u>Elevated Release</u>
<u>Possible Modeling Use:</u>	Similarity Theory	Statistical Theory
<u>Basic Measurement:</u>	Wind speed, temperature, and temperature difference	
Height:	10m	
Location:	Representative surface	
Response time:	(Primary variables)	1 min
Sampling duration:	(Primary variables)	3 min - 1 hour
Accuracy	(Primary variables)	u: 5%; 0.2 m/sec threshold T, ΔT: .01°C
<u>Influence:</u>	Through profile equations	
<u>Method of Deriving variable:</u>		

$$(1) \text{ direct; } L = \frac{u_*^2 T}{kg T_*}$$

$$(2) \text{ indirect; } \frac{h}{L} = Ri_B \frac{k F^2 \left(\frac{h}{z_0}, \frac{h}{L}, \frac{z_0}{L} \right)}{G \left(\frac{h}{z_0}, \frac{h}{L}, \frac{z_0}{L} \right)}$$

by successive approximation

- Recommendations:
- (1) NWS add ΔT to routine observation.
 - (2) Industrial sites: Measure Ri_B

EXHIBIT 2.7: HEAT FLUX (H_F)

Possible Modeling Use:

$$w_* = \left[\frac{g}{T} \frac{H_F}{\rho C_p} h_c \right]^{1/3}, \text{ Mixed-layer similarity}$$

$$L = -u_*^3 \rho C_p T / kg H_F \text{ Monin-Obukhov similarity}$$

Lower boundary conditions for numerical PBL models

Basic Measurement:

Height: 10 m or less
Location: Representative surface
Sampling duration: 20-60 min

Measurement Technique:

(1) Eddy correlation $H_F = \rho C_p w' T' = -\rho C_p u_* T_*$
Instrument Response: $nz/u < 3$, unstable
 $nz/u < 5$, neutral
 $nL/u < 10$, stable

Accuracy: 10%, homogeneous terrain
Comments: requires research grade instrumentation

(2) Dissipation Technique:

$$X_\Theta = \frac{u_* T_*^2}{kz} \phi_x$$

where,

$$\phi_x = \begin{cases} 1.48 (1 - 9Z/L)^{-1/2}, & Z/L < 0 \\ 2 (0.74 + 4.7Z/L), & Z/L > 0 \end{cases}$$

a. Direct Dissipation:

$$X_\Theta = 6D \overline{\left(\frac{\partial \Theta}{\partial x} \right)^2} = \frac{6D}{u^2} \overline{\left(\frac{\partial \Theta}{\partial t} \right)^2}$$

Instrument Response: 103 - 104 Hz
Accuracy: 20%, limited by knowledge of ϕ_x
Comments: Requires highly specialized instrumentation and analysis.

b. Inertial subrange dissipation:

$$S_{\Theta\Theta}(k_1) = 0.4 X_{\Theta} \epsilon^{1/3} k_1^{-5/3}$$

Instrument response: 10 Hz

Accuracy: as for 2a

Comments: Requires research grade instrumentation

c. Structure Function

$$\overline{[T(x) - T(x+r)]^2} = C_T^2 r^{2/3}$$

$$X_{\Theta} = 0.44 C_T^2 (C_v^2)^{1/2}$$

Instrument response: ?

Accuracy: As for 2a

Comments: May use path averaging of optical scintillations

3. Profile Method:

$$u_* T_* = \frac{u_* k z}{\phi_h} \frac{\partial \Theta}{\partial z}$$

$$= u_* k (\Theta_2 - \Theta_1) / (\ln(z_2/z_1) + \psi_h(z_2/L) - \psi_h(z_1/L))$$

Instrument response: 1 min

Accuracy: 20%

Comments: Requires a minimum of 2 temperature measurements (10 m and 2 m)

(4) Surrogate Method: $H_F = f(\sigma_T)$

Instrument response: as for eddy correlation

Accuracy: depends on knowledge of $f(\sigma_T)$

Comments: Easier than eddy correlation since do not need to measure w.

(5) Surface Energy Budget:

$$\text{Soil Heat Flux} = \text{Net Radiation} + \text{Sensible Heat Flux} + \text{Latent Heat Flux}$$

Instrument Response: 1 min

Accuracy: 20% ?

Comments: Requires measurements or assumptions
equally as restrictive as other methods

Influence of derived
variable on accuracy

of model variables: $E(w_*) \sim E(H_F)/3$

$E(L) \sim E(H_F)$

where E is "error"

Recommended Method: Profile or surrogate method

EXHIBIT 2.8: PASQUILL-GIFFORD STABILITY CLASS

	<u>Ground Level Release</u>	<u>Elevated Release</u>
<u>Possible Modeling Use:</u>	Gaussian type statistical	
<u>Basic Measurement:</u>		
Height of Measurement	N/A (Surface variable)	
Location:	Representative surface	
Interrogation Interval:	N/A	
Time Constant:	N/A	
Representative Interval:	1 Hour	
Accuracy:	Wind Speed: 0.2 m/s +5% Cloud Cover: 20% Day: No error Hour: No error Ceiling Height: 20% Alternative - Upward Heat Flux: 20% Incoming Solar Radiation: 20%	
<u>Accuracy of Derived Variable:</u>	P-G: One class Smith P: 0.2-0.4 Variations in P (range 0-7)	
<u>Influence of Derived Variable on Diffusion Calculation*:</u>	at 500 m: Factor of 1.8 to 2.7 at 10 km: Factor of 1.7 to 5.4	Factor of more than 100 Factor of 1.7 to more than 4

Method of Deriving
Variable:

Processing of Input Variable Values in Computer
Program.

Recommendation:

In general, other more direct measures for estimating dispersion (one for horizontal, one for vertical) are preferred. However, for the time period where models that require the P-G class as an input variable are in use, the F.B. Smith (1972) technique should be used to generate the continuous variable P (which can be converted to P-G class, if necessary).**

*Using P-G curves

**Because of the range of dispersion that may be associated with any given condition, air quality estimates made using this variable should have error bounds reported with the estimate.

3. DISCUSSION OF DERIVED VARIABLES

Wind Sigmas (σ_u , σ_v , σ_w , σ_θ , σ_ϕ)

The opening discussions of derived variables were focused upon the standard parameters derived from measurements of wind velocity components. These include σ_u , σ_v , σ_w , σ_θ , and σ_ϕ , which are often treated as if they were direct measures of turbulence, rather than as statistically derived parameters. The relationships between the rectilinear components and the magnitude of the mean wind vector u_r and the polar component forms are:

$$\sigma_u \approx \sigma_v \approx u_r \sigma_\theta$$

$$\sigma_w \approx u_r \sigma_\phi$$

Studies of 0.2-second observations for 40-minute periods by Weber et al. (1975) show that for wind speeds between 2 and 10 m/sec, the following correlations were very good (regardless of stability):

$$\sigma_w/\sigma_\phi \text{ vs } u \text{ and } \sigma_v/\sigma_\theta \text{ vs } u.$$

On the other hand, σ_u/σ_ϕ or σ_u/σ_v appears to be a weak function of stability:

$$\sigma_u/\sigma_v = 1.5 \text{ for stable, } \sigma_u/\sigma_v \sim 1 \text{ for nonstable.}$$

σ_ϕ is most important near elevated sources and for evaluation of extreme cases which are of importance in regulatory and operational decisions. For predicted averages or modeling ensembles, the u_* estimate is a more effective parameter to establish than σ_ϕ .

The adequacy of all of these relationships for wind speeds less than 2 m/sec was questioned. The use of velocity component range to estimate values for any of the σ 's was recommended only as a last resort (when specific statistical calculations were impracticable). The ratio of the range to the standard deviation has been found to be a function of both stability and measurement height. This suggests that large errors may result unless corrections are undertaken. A range estimator is sometimes, however, the only practical method when large quantities of historical strip chart data are the only records of wind variation. Use of Pendergast and Crawford (1974) results can help reduce the error in this process.

A question about the importance of sensor response to the precision of the concentration estimate to be derived from use of these σ 's was raised. As long as the sampling time exceeded the plume travel time to the receptor of interest, the uncertainty introduced by smoothing the high frequency contributions is not often significant for Gaussian model estimates. Where the high frequency component is of particular interest, a synthetic restoration technique (e.g., Pasquill 1976) may be used.

The question of recording both mean wind component values and turbulence parameters for a time interval shorter than an hour was considered. Comparison of exposures due to, and with historical modeling of, puff releases as well as for releases under low wind speed conditions with wide ranging wind direction changes (Sagendorf and Dickson 1974) have shown the utility of these intermediate averages. A 3-minute period was tentatively suggested as a useful duration. This corresponds to the period for which the σ_y predictions were made in the studies leading to the original P-G dispersion curves (Pasquill 1976). Specific applications and instrumentation will determine the selection of this intermediate period for particular sites. The 3-minute period represents a compromise that allows an adequate number of high frequency digital samples (of order 1 to 0.1 Hz) to be used in the computation of this intermediate mean and variance so that sampling errors are often tolerable. In addition, hourly averages can be simultaneously recorded or can be estimated from 20 of these 3-minute values.

The relative value of measuring σ_w or σ_ϕ , rather than estimating it from heat flux or other surface boundary layer (SBL) parameters was discussed. The reliability of sonic anemometry was discussed in this regard; it appeared that for σ_w (single vertical axis) measurements, the reliability of sonic measurements is not yet equivalent to that of mechanical wind sensors.

The Lagrangian time scale is recognized to be important (especially with increasing time of travel), however, at present there is a large difference in the value as determined from diffusion or turbulence measurements. Until this difference is resolved, it may not be appropriate to perform routine estimates. Further research is needed to determine the ultimate reliability and usefulness of turbulence-derived estimates of this parameter.

Roughness Parameter (z_0)

Together with u_* , z_0 incorporates the effect of the small-scale surface irregularities on turbulent transfer processes in the atmospheric surface layer. It is usually involved in the integral forms of the flux-profile relations in the surface layer. In diffusion models, only the Lagrangian similarity theory relations explicitly involve z_0 or rather $\log z_0$.

Since z_0 is basically defined as a parameter in the logarithmic wind profile law

$$\bar{u} = (u_*/k) \ln (z/z_0) \quad (B-1)$$

for a neutral surface layer over a homogeneous surface, it is best determined from wind profile measurements in the part of the surface layer above the tops of the various roughness elements.

An indirect way of determining z_0 , which does not require wind profile measurements, is through the use of previously developed empirical relations between z_0 and some of the measurable physical characteristics of the surface, such as the mean height (h_0) and area density of the predominating roughness elements. For example, on

the basis of profile derived z_0 values for various types of natural surfaces, Lettau has proposed an empirical relation

$$\log z_0 = 1.19 \log h_0 - 1.24 \quad (B-2)$$

in which z_0 and h_0 are both expressed in cm. According to Equation B-2, the ratio h_0/z_0 varies from 4 for tall forests to 27 for sands. Actually, z_0 also varies with the area density and shape of roughness elements and, for very flexible roughness, on the mean wind speed near the top of the elements. But these factors are implicitly involved if one is using an empirical relation of the type in Equation B-2 based on the actual observations involving the same type of surface elsewhere.

There are not enough direct (based on wind profile) measurements of z_0 over urban areas, from which an empirical relation of z_0 as a function of h_0 and area density (λ) can be obtained. Some guidance is given by wind tunnel measurements by Counihan (1971) using Leggo blocks as roughness elements (model buildings). His results show that z_0/h_0 when plotted as a function of λ , at first increases, attains a maximum value for certain density, and decreases monotonically with the further increase in λ . More measurements of this type are needed for other types of roughness elements. These can be used to test some of the relations that have been proposed (Lettau 1969; Businger 1974) on the basis of purely geometrical considerations.

The foregoing discussion mainly applies to a more or less flat and homogeneous surface. Many natural surfaces of interest in diffusion modeling are not homogeneous. In a strict sense, z_0 may not be defined if the wind profile in the neutral surface layer deviates too much from its logarithmic form. When the roughness characteristics of an inhomogeneous surface are to be expressed in terms of single length parameter, for the sake of simplicity, an effective roughness z_{0e} may be defined. For example, Fiedler and Panofsky (1972) defined z_{0e} as "that roughness length which homogeneous terrain would have in order to produce the correct space-average downward flux of momentum near the ground, with a given (space-averaged) wind." They suggested that an instrumented aircraft

could be used for measuring the area-averaged u_* and $\bar{u}$ for determining z_{0e} . The above concept of effective roughness can be used for a rolling terrain in which the topographical features are not more than 100 m or so. The roughness parameter z_0 or z_{0e} , would not be relevant in a more complex (hilly) terrain. For that matter, the similarity theory relations in which this parameter is involved would not be valid either.

In some diffusion calculations, a water (large lake or sea) surface may be involved. Unlike that over a land surface, z_0 is a variable parameter which depends on the wave field, which in turn depends on the stress (τ) on the surface or u_* , fetch, etc. For a fully developed wind wave field (waves in equilibrium with the prevailing winds), Charnock (1955) proposed the relation

$$z_0 = b \frac{u_*^2}{g} \quad (B-3)$$

where b is a constant ($b = 0.02$). From a large number of observations over the oceans, the above relation has been shown (Garratt 1977) to work well within a factor of two. It has the simplicity of not requiring any measurements of the sea state (wave height, phase velocity, etc.).

Richardson Number (Ri_f , Ri_c , Ri_B)

The vertical gradient of potential temperature is sometimes used to determine atmospheric stability for diffusion computations. This parameter, however, is not a complete description of atmospheric stability as it ignores the effects of wind shear. The nondimensional flux Richardson number Ri_f , which arises from the turbulent energy equation, however, does incorporate both effects and is given by

$$Ri_f = \frac{gH_F}{C_p T \tau \partial u / \partial z} \quad (B-4)$$

This parameter represents the ratio of the rate of dissipation of turbulent kinetic energy by buoyancy to its rate of production by the shear stress. Its sign is dependent on that of H_F and it is positive/zero/negative in stable/neutral/unstable atmospheres, respectively.

Evaluation of Ri_f in the surface boundary layer (SBL) requires measurements of the turbulent heat flux H_F , the Reynolds shearing stress τ , as well as the vertical wind shear $\partial u / \partial z$. Of course, the vertical heat flux ($\overline{\alpha'w'T'}$) can be parameterized by $\overline{u_*T_*}$ and the shearing stress ($\overline{\alpha u'w'}$) can be parameterized by u_*^2 , if these parameters can be obtained by some other means.

If gradient transport theory is used, Ri_f can be given by

$$Ri_f = \frac{g}{T} \frac{\partial \theta / \partial z}{(\partial u / \partial z)^2} \frac{K_H}{K_M} \quad (B-5)$$

but this form requires knowledge of K_H/K_M which is somewhat difficult to determine, as is discussed below. Thus the gradient form of the Richardson number defined as

$$Ri = Ri_f \frac{K_M}{K_H} = \frac{g}{T} \frac{\partial \theta / \partial z}{(\partial u / \partial z)^2} \quad (B-6)$$

is in a form which can be evaluated by observations of T and u at two levels of a tower from the finite difference form of the Richardson number Ri_Δ given by

$$Ri_\Delta = \frac{g}{T} \frac{\Delta \theta}{(\Delta u)^2} \Delta z \quad (B-7)$$

However, small errors in the velocity observations, especially in low speed conditions, can lead to erroneously large values of Ri, and thus the bulk form of the Richardson number Ri_B is evaluated from

$$Ri_B = \frac{gh}{T} \frac{[\theta(h) - \theta(Z)]}{[u(h)]^2} \quad (B-8)$$

where h is the depth of the SBL or convective boundary layer and Z is some convenient level near the surface, such as 2 m. For surface releases it is recommended that Ri_B be used as a stability parameter which can be used to evaluate the Monin-Obukhov length in a SBL (Irwin and Binkowski 1980).

In modeling elevated releases in the region of the planetary boundary layer (PBL) above the SBL, Ri_Δ has been used to estimate the local stability of the PBL even though there is no theoretical basis for using Ri in the PBL. In addition, problems arise in the evaluation of Equation B-7 in the area of low level jets associated with surface and elevated stable layers, as in this region the shear goes to zero and Ri becomes an extremely large positive value.

However, observations of the mixing in the region of the low level jets has shown that mixing is great in this area. Similar results have been found using turbulent closure models. Thus perhaps, the following form of Ri_B could be used to evaluate the stability of the PBL under these conditions:

$$Ri_B' = \frac{g}{T} \frac{\Delta \theta}{(u_{1/2})^2} \Delta Z, \quad (B-9)$$

where $u_{1/2}$ is the wind halfway between the levels of the two temperature measurements. This situation could arise during lofting plume situations.

A problem also arises during daytime convective conditions when a constant potential temperature PBL caps a superadiabatic SBL. Use of Equation B-7 to represent the local stability of the PBL will give a

$Ri \approx 0$, but convective elements passing through the PBL from the SBL will be causing a great deal of mixing. Thus, the amount of mixing in the PBL under these conditions might better be estimated from the SBL value of Ri_B as determined from Equation B-8. This situation could arise during fumigation conditions.

Friction Velocity (u_*)

u_* is the relevant velocity scale for modeling vertical dispersion in the surface layer, i.e., $z = 0 (|L|)$. However, it is not clear that u_* determines the crosswind spread in the surface layer. For emissions generated by saltation of loose particles on roads or tailings, u_* determines the emission rate. There is some evidence to show that the emission rate is proportional to u_*^3 .

Eddy correlation techniques to measure $-\overline{u'w'}$ can be used in field studies. For operational use, profile measurements of temperature and wind at two or three levels below 10 m can be used to derive acceptable estimates of u_* .

Convective Velocity Scale (w_*)

w_* determines vertical and horizontal spread of plumes released in the mixed layer. There is some evidence to show that σ_v in the surface layer is also proportional to w_* .

As $w_* \propto Q_0^{1/3}$, surrogate methods to estimate Q_0 , the surface temperature flux, are well suited for most applications. For example, the relationship between σ_T and Q_0 in the unstable boundary layer can be exploited for deriving acceptable values of w_* . Even an aircraft equipped with a simple temperature sensor can be used to measure σ_T , which is related to Q_0 by

$$Q_0 = \left(\frac{\sigma_T}{1.35} \right)^{3/2} \left(\frac{gz_a}{T} \right)^{1/2}$$

where z_a is the altitude of the aircraft traverse. z_a should be less than $0.1 h_c$ for the relationship to hold. This method of

measurement (field studies only) has the advantage of being able to yield an area averaged Q_0 or w_* which is what an elevated plume "sees."

Recent studies indicate that acceptable estimates of Q_0 and hence w_* can be obtained from rugged optical and acoustic sensors to measure C_T^2 and C_n^2 .

Simple modeling (see Venkatram 1978) shows that w_* can be expressed as

$$w_* = A Q_m^{1/2} F\left(\frac{t}{\pi}\right)$$

where Q_m is the maximum surface temperature flux whose half period is π . The variable A varies within very narrow limits and can be essentially treated as a constant. This is very useful as we can estimate w_* from Q_m with little knowledge of other boundary layer variables. Q_m can be estimated from surrogates such as the incoming solar radiation if direct measurements are not available.

The measurement of h_c has been discussed by another group.

Monin-Obukhov Length (L)

Within the surface layer, the dynamic effects of heat cannot be neglected as in the dynamic sublayer beneath it. Consequently, additional parameters are available to form velocity, length, and temperature scales. The parameters can be combined to form a length scale $L = -(u_*^3 T) / (k g w' T')$, the Monin-Obukhov length.

Similarity theory based on this scale and u_* and T_* indicates that nondimensional profiles of velocity, temperature, and local statistical quantities should be universal functions of the nondimensional height, z/L .

Since the length scale may also be defined as $L = (u_*^2 T) / (k g T_*)$, its value can be computed from basic turbulence measurements used to evaluate shear stress and heat flux. This is the direct measurement method.

The indirect computation relies on measurements of wind speed and temperature (as well as temperature difference) in the surface layer. Specifically, the bulk Richardson number is used in conjunction with known integrals from the profile laws of similarity theory (Paulson 1970; Nickerson and Smiley 1975; Benoit 1977) through the relation:

$$\frac{h}{L} = Ri_B \frac{k F^2}{G}$$

where

$$F\left(\frac{h}{z_0}, \frac{h}{L}, \frac{z_0}{L}\right) = \frac{u_h}{u_*}$$

$$G\left(\frac{h}{z_0}, \frac{h}{L}, \frac{z_0}{L}\right) = \frac{\Delta\theta}{T_*}$$

and where h is layer over which Ri_B is measured. The solution for L is obtained through successive approximations, and current techniques show (Irwin et al. 1980) that the indirect procedure produces an estimate within 25% of that obtained using the direct methods for $L > h$ with research grade instrumentation (i.e., Kansas, Minnesota). When $L < h$, the indirect method is within a factor of two. It is recommended that the simpler measurements required by the indirect method be obtained and used to compute both Ri_B and L .

Pasquill-Gifford Curves and Stability Categories

The Pasquill-Gifford method of expressing the Gaussian diffusion parameters σ_y and σ_z as a function of stability categories A through F is presently among the most widely known and used schemes in preparing dispersion estimates of windborne material. The original version of this practical system, presented by Pasquill (1961), was intended for determining tentative estimates of vertical plume spread in open country for the six stability categories A-F and for 3-minute sampling time. The stability categories were subjectively specified in terms of surface wind speed, insolation, and cloud cover. Rough estimates of plume spread were also suggested as a function of horizontal wind direction variation and of the stability classes.

Gifford (1961) modified Pasquill's plume spreading data into a family of curves of standard deviation σ_y and σ_z , also expressed as a function of the same stability categories and distance from the source. The P-G curves were later published by Turner (1970) in a workbook on dispersion estimates.

With the rapid increase in application of this popular scheme for obtaining σ_y and σ_z , particularly after the introduction of the "STAR" computer program, there also appears to have been a tendency among the users to overlook the limitations of this system imposed by the original data base. The original Pasquill curves had a rather limited data base, dealing with vertical plume spread data at distances less than 1 km and with speculative extrapolations for stable conditions at distances greater than 1 km. The intended use of the Pasquill curves were to provide tentative estimates of dispersion parameters in the absence of turbulence-related observational data (wind fluctuations).

Because of the increased use (and misuse) of the P-G classification system in critical environmental impact evaluations, the system has been subjected to increased scrutiny by the technical and legal community. This workshop represents the fourth scientific group which has conducted a critical review of the applicability of the P-G curves and classifications during the past 3 to 4 years. A summary of some recommendations which have emerged from these meetings are given below.

At the 1977 Chicago Specialists Conference on EPA Modeling Guideline (Roberts 1977), the working group II-4 stressed that a number of questions regarding the use of P-G curves and stability classification deserve serious attention and systematic study. Significant discrepancies were noted between P-G stability categories and those derived from tower ΔT . The latter was recognized as not being representative of the key factors responsible for turbulence. The P-G curves of σ_z were also questioned strongly with suggestions that for tall stack emissions, stability A and, to some extent, stability B curves may result in large overestimates of short-term ground-level concentrations. It was also recommended that "STAR"

program stability classifications must be supplemented by detailed specification of vertical wind and temperature profiles, including mixing height data.

At the 1977 AMS Workshop on Stability Classification Schemes and Sigma Curves (Hanna et al. 1977), recommendations were made that σ_y should preferably be estimated from wind direction fluctuation σ_θ , as recommended earlier by Pasquill (1961). Adjustments should also be made to account for surface roughness and urban heat island effect by changing the stability class by one unit in the direction of unstable to account for these effects. Regarding σ_z it would be preferable to use σ_θ as a measure of vertical dispersion; ΔT is only useful in stable conditions and only when measured sufficiently near the surface.

The EPA 1979 Workshop on Atmospheric Dispersion Models in Complex Terrain (Hovind et al. 1979) expressed the concern of determining terrain effects upon σ_y and σ_z . Regarding future attempts to improve Gaussian models in complex terrain applications, it was suggested that on the basis of field studies a matrix be developed which will consider effects of changes in model variables, such as P-G stability classification, upon proposed improvements in the models.

Rather than rely on the single P-G stability class for both horizontal and vertical dispersion estimates, separate dispersion related variables for horizontal and vertical dispersion are discussed elsewhere in this document. However, before models which use these variables directly become available as "guideline" models for regulatory purposes, it is still desirable to have an hourly P-G stability class so that current models may be used. Also, after new models become available, it may still be desirable to have input information for old models so that they may be executed for comparison purposes.

The seven class stability value can be inferred from hour of day and day of year (so that solar elevation angle can be obtained), and from hourly observations which include cloud cover, ceiling height, and 10 meters wind speed. Pyranometer measurements can replace the cloud observations and solar angle during the day.

An alternative has been suggested by F. B. Smith (1972) which determines a continuous stability variable, P , which can have real values between 0 and 7. Any value of this variable can be converted to the 7 class stability value above. Variables required are 10 meter wind speed and upward heat flux. Alternate variables for the upward heat flux are incoming solar radiation by day and cloud amount at night.

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APPENDIX C

MEASUREMENT TECHNIQUES - METEOROLOGICAL VARIABLES

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1. INTRODUCTION

Two general instrument classifications are made: conventional tower or mast-mounted instrument and the remote instrument or non-ground-attached system (balloons, aircraft, etc.). The following variables were considered.

Scalar mean, harmonic mean, and vector mean wind speed

(u_s, u_h, u_v) (m/s)

Wind direction (θ, ϕ) (degrees arc)

Wind components

along mean wind component (u) (m/s)

crosswind component (v) (m/s)

vertical component (w) (m/s)

Temperature (T) ($^{\circ}\text{C}$)

Temperature difference (ΔT) ($^{\circ}\text{C}$)

Dew point temperature (T_d) ($^{\circ}\text{C}$) or relative humidity
 $(\text{RH})(\%)$

Radiant flux density (Q^*) (W/m^2)

Atmospheric pressure (p) (kPa)

Precipitation (P) (mm)

Convective mixing layer height (h_c) (m)

Mechanical mixing layer height (h_m) (m)

The following conclusions apply to measuring each of these variables:

- 1) Data should represent a 60-minute interval labeled by the ending time (Julian date, hours, and minutes in local standard time in the range 0001 to 2400).
- 2) The number of samples taken and the process by which they are combined are functions of the variables and the data application (described with each variable). No less than half the prescribed number of samples may be used to represent the hour.

- 3) Siting of the instrument is often the most important consideration and should be made by an experienced meteorologist.
- 4) A vigorous quality control and assurance program is required to achieve valid data to the specifications described below and in a sufficient quantity to represent long periods of time (months to a year) without bias.

In addition to these general recommendations, a summary of measurement-specific information is presented here by variable category. The summaries include acceptable levels of accuracy, resolution, and response time which are considered both achievable and sufficient for hourly dispersion applications. Detailed discussions of the measurement techniques are addressed in Sections 3 and 4 for surface and tower measurements, and remote measurements, respectively.

Flow Measurements

Tower and mast-mounted (10 m is standard height for wind measurements):

Anemometers (cup or propeller) (for $\bar{u}_s$, $\bar{u}_v$, $\bar{u}_h$, u , v , w)

Starting Speed (within accuracy)	≤ 0.5 m/s
Distance Constant (63% recovery)	≤ 5 m
Accuracy	≤ 0.2 m/s +5% of speed

Wind Vanes (for $\bar{\theta}$, $\bar{\phi}$, σ_{θ} , σ_{ϕ})

Starting Speed (10° displacement)	≤ 0.5 m/s
Damping Ratio	≥ 0.4
Delay Distance (50% recovery)	≤ 5 m
Accuracy	$\leq 5^\circ$
Resolution	$\leq 1^\circ$

Sampling

Sixty or more samples will estimate the mean within 5 to 10%.

Three hundred and sixty or more samples will estimate the standard deviation within 5 to 10%.

Note: the effective resolution of 360 samples of a 1° measurement resolution is $0.05^\circ = 1^\circ/(360)^{1/2}$. Also the resolution is the best estimate of accuracy of a relative measurement such as the distribution about a mean.

Computations

Wind Speed (horizontal)

Both the scalar mean ($\bar{u}_s$) and resultant vector average ($\bar{u}_v$) should be reported. The harmonic mean ($\bar{u}_h$) is preferred for initial dilution and plume rise calculations.

$$\begin{aligned}\bar{u}_s &= \frac{1}{N} \sum_{i=1}^N u_{s_i} \\ \bar{u}_v &= \left[\left(\frac{1}{N} \sum_{i=1}^N u_i \right)^2 + \left(\frac{1}{N} \sum_{i=1}^N v_i \right)^2 \right]^{1/2} \\ \bar{u}_h &= \left(\frac{1}{N} \sum_{i=1}^N \frac{1}{u_{s_i}} \right)^{-1}\end{aligned}$$

Wind Direction (horizontal)

The directions should be reported as the hourly resultant vector direction

$$\bar{\theta} = \arctan \bar{v}/\bar{u} \text{ when } u \text{ is oriented north}$$

Standard Deviations

For any variable, X, representing one of at least 360 samples of horizontal wind direction (θ), vertical wind direction (ϕ), vertical wind speed (w), scalar wind speed (u_s), or the reciprocal of the scalar wind speed ($1/u_s$) the standard deviation may be calculated from

$$\sigma_x = \left[\left(\frac{\sum (x^2)}{N} \right) - \left(\frac{\sum x}{N} \right)^2 \right]^{1/2}$$

Note that the 360° to 1° crossover in θ must be accounted for when σ_θ is computed from a single vane system.

When digital methods are used, the accuracies mentioned above will be achieved. The adequacy of analog computers for this purpose was not estimated.

Indirect Measurements

The only commercially available monitoring system for indirect flow measurements is the Doppler acoustic radar. Other techniques are used experimentally. Accuracy of the 20-minute mean orthogonal components u , v , and w is estimated at 0.5 m/s. Resolution for σ_w is 0.1 m/s. Reliable range is 50 m to 600 m with 1,000 m exceeded under ideal conditions. Height resolution is 30 m.

Temperature Measurements

Ambient Temperature (T)

When a good-quality aspirated radiation shield is used measurements with a variety of transducers can be calibrated and operated to provide

Accuracy	$\leq 0.5^{\circ}\text{C}$
Resolution	$\leq 0.1^{\circ}\text{C}$
Time Constant (63%)	~ 1 minute

Temperature Difference (ΔT or $T_{z2} - T_{z1}$)

Two identical aspirated radiation shields equally exposed will provide a ΔT (a relative measurement) value to accuracies proportional to the effort exerted in selection and calibration. Resolution should be one-fifth the accuracy.

	<u>Readily Obtained</u>	<u>Research Effort</u>
Accuracy	$\leq 0.1^{\circ}\text{C}$	$\leq 0.05^{\circ}\text{C}$
Resolution	$\leq 0.02^{\circ}\text{C}$	$\leq 0.01^{\circ}\text{C}$
Time Constant (63%)	1 minute	

Dew Point Temperature (T_d)

Humidity may be measured in a variety of ways. Methods other than dew point measurements should meet the equivalent dew point accuracy stated here. The saturated salt technique is acceptable for all dispersion applications. It provides:

Accuracy	$\leq 1.5^{\circ}\text{C}$
Range	$- 30^{\circ}\text{C}$ to $+20^{\circ}\text{C}$
Resolution	$\leq 0.1^{\circ}\text{C}$
Time Constant (63%)	~ 30 minutes

An accuracy of 1°C will probably result from careful use.

Sampling

The sample averaging time need be no shorter than half the time constant. Shorter intervals may be used for conformity with other variables.

Solar Radiation

A measure of global sun and sky radiation can be made using good-quality pyrometers which provide the following performance:

Accuracy	$\leq 50 \text{ w/m}^2$
Resolution	$\leq 10 \text{ w/m}^2$
Time Constant (63%)	$\sim 5 \text{ sec}$

Atmospheric Pressure

The standard atmosphere pressure for the station elevation will often be of sufficient accuracy to represent true pressure for dispersion applications.

Accuracy	$\leq 1 \text{ kPa (10mb)}$
Resolution	$\leq 0.2 \text{ kPa (2 mb)}$

Precipitation

Measurements are highly sensitive to wind speed. Use of a shield and placement in a sheltered location is highly desirable.

Accuracy	1-6% depending on precipitation rate
Resolution	0.2 mm water equivalent

Height of the Mixed Layer

Convective Mixed Layer

From the position of a monitoring requirement the monostatic acoustic radar (or Doppler version) was considered as the only technique commercially available.

Accuracy	~ 50 m
Resolution	~ 10 m monostatic radar ~ 30 m Doppler
Range	50 m - 500 m usually 50 m - 800 m often 50 m - 1,000 m sometimes
Time Constant	~ 10 sec monostatic radar ~ 20 minutes Doppler

Mechanical Mixed Layer

Since the range of this phenomenon is approximately 0-200 m, it may sometimes be estimated from tower data. Remote techniques may be used (such as acoustic radar) if they are modified for limited range. Such instruments are not currently available commercially.

2. SURFACE AND TOWER FLOW MEASUREMENTS

2.1 Wind Speed and Direction

Wind speed and direction, or wind velocity (a vector) can be measured with accuracy acceptable for dispersion modeling with commercially available instrumentation.

Surface wind velocity measurements should be measured at 10 m. The area surrounding the instrument should be clear of obstructions to flow for a distance equal to 10 times the height of such obstructions.

Wind speed and direction instrumentation may also be mounted on open towers at any desired height. The instrument should be mounted on a boom which holds it at a sufficient distance from the tower such that it is outside the major influence of the tower. A useful rule-of-thumb for this is a distance of 2 times the diameter of the tower. Instruments should not be mounted on chimneys or other solid structures.

Satisfactory wind speed and direction measurements can be made using cup anemometers and wind vanes, wind vanes with propeller anemometers mounted on the front, or with two or three (for vertical wind speed) propellers mounted on orthogonal axes.

Wind vanes should have a starting speed of 0.5 meters per second or less, a damping ratio of at least 0.4, and a delay distance of 5 meters or less, which refers to responses resulting from 10° deflections. For such vanes, an absolute accuracy of 5° with a resolution of 1° can be expected with reasonable care and an acceptable quality assurance program.

Anemometers should have a starting speed of 0.5 meters per second or less, and distance constant of 5 meters or less. An accuracy of $0.2 \text{ m} \pm 5\%$ of the measured value can be expected with an acceptable quality assurance program.

For better definition of the flow field, the use of several appropriately sited sets of instruments is highly recommended.

With normal atmospheric variability, a set of 60 samples should give a mean value within 5 to 10% of the true value. Approximately 360 samples are required for a similar accuracy for standard deviations.

Wind speed should be reported as vector, scalar, and harmonic means. The difference between vector and scalar means should be noted to indicate major fluctuations in the wind directions over the sampling period. Wind directions should be reported as the vector mean direction.

Digital computation is the preferred method for determining standard deviations of wind speed and direction. The adequacy of analog computers for this purpose cannot be estimated by the panel.

Vertical Velocity

Vertical velocity is measured most conveniently with a vertical propeller anemometer, mounted apart from any other instrumentation. Because the instrument is often operating at the lower extreme of its range, and because the elevation angle of the wind vector is frequently slight, meaning that propeller is operating at yaw angles where it is least accurate, the accuracy of the vertical velocity measurement may be poor. (Careful alignment of the propeller axis with respect to the vertical is therefore imperative.) Bivanes may be used to measure the elevation angle, but they require frequent maintenance and calibration, do not give reliable information during precipitation, and are, in the opinion of the panel, more of a research than an operational instrument.

Sonic, hot film, and other such anemometers should also be considered research tools, excellent for micro-turbulence studies, but not desirable or practical for air pollution diffusion studies at this time.

The recommendation of the panel to the NWS is that they adopt the F460 anemometer and vane system as soon as practical.

2.2 Temperature

The state-of-the-science for temperature measurement independent of the medium is well advanced. Good quality linear thermistors or platinum resistance devices are quite adequate and cost effective for measuring this variable in air. One could use quartz crystal thermometers if greater transducer accuracy were desired, but they are relatively expensive and not as reliable for long-term use, making them more suitable for research purposes. Thermocouples may be suitable for ambient temperature measurement, but are not recommended due to the increased difficulty in operating them. In any case, it should be recognized that the limitations placed on the accuracies for T or ΔT stem primarily from the difficulties in adequately shielding the sensor.

Ambient temperature can be measured to an accuracy of 0.5°C with a resolution of 0.1°C , provided a good-quality aspirated radiation shield is used. Experience has shown that under all conditions, a downward-facing shield with the sensor unable to sense the ground but being in a flow in excess of 2.5 meters per second⁻¹ provides for the greatest accuracy (McTaggart-Cowan and McKay 1976). The sensor should be lagged to provide a time-constant of approximately 1 minute when in the shield-flow. If this is done, a 60-minute average value is obtainable with a minimum of 60 equally spaced samples. In maintaining consistency with World Meteorological Organization (WMO) standards for ambient temperature, we recommend that the shield be located at the 2 m height. It is recognized that some models may be based on temperatures at 10 m but this value may be readily calculated by using the more critically needed variable of ΔT measured between 2 and 10 m.

ΔT should be measured with a completely separate system from T . Two and ten-meter heights for the shields are considered to be the standard elevations for this measurement in addition to being the most readily available, although it is recognized that in some applications the lower-level shield may be located at 10 m or any other elevation. If this latter situation occurs, it must be recognized that the accuracy and resolution figures below must be related to a

considerably greater shield-separation due to the less rapid change of temperature with height at that level. The accuracy and resolution that can be readily obtained for ΔT are 0.1°C and 0.02°C , respectively. Considerable care will allow these measurements to be reduced to 0.05°C and 0.01°C . The time constant and sampling interval are the same for ΔT as for T . Because of this, σ_T , a variable required in some models, cannot be meaningfully measured with the above T or ΔT systems. A much shorter time-constant device will be required which would not be suitable for standard network use but could be used in research applications. Hot-wire probes, sonic thermometers, platinum wire systems, and small bead thermistors would be most likely choices in this case (Kaimal 1975).

Siting for temperature variable measurements must be done carefully. Care must be taken to maintain the integrity of ambient environment, particularly the surface very near the tower.

To maintain precision and accuracy in these systems, a rigorous quality control program is required. This program should consist of frequent operational checks and routine shield maintenance and sensor calibrations dependent on the environment at the site.

2.3 Humidity

Humidity, defined as vapor pressure, represents a variable constituent of air. By volume, water vapor can vary from 0 to 4%. Relative humidity, one of the terms that describe humidity, is a dimensionless number determined by dividing the vapor pressure by the saturation vapor pressure and multiplying by 100 to obtain a percentage. Dew point, another term describing humidity, is defined as the temperature to which air must be lowered in order for it to be saturated; it is the preferred measurement for tower installations.

For a 10 m or taller tower, the present choice for a dew point sensor is between the dew-cell technique and the cooled-mirror technique. A measurement accuracy of $\pm 1.5^{\circ}\text{C}$ over the temperature range of -30° to 20°C is recommended. The time constant of the system can be anywhere from 1 to 30 minutes, but for some applications such as fog formation in cooling tower studies, it may be necessary to

use an instrument with a time constant considerably shorter than the 30-minute maximum.

The dew cell, a generic term that describes an instrument which operates on the principle of the saturation vapor pressure of lithium chloride, is moderately priced and less complex than the cooled-mirror device. It should be installed in a weather shield that offers protection from solar radiation and wind. Some miniaturized sensors, designed without sufficient protection from the cooling effect of wind or the heating effects of solar radiation are susceptible to large errors. Lithium chloride, the salt used in this sensor, undergoes recognizable phase changes (Acheson 1963), but over the range of most interest, these are not too troublesome. At some locations where atmospheric pollution is high from "poisoning" chemicals, the dew cell error increases. Frequent cleaning and recharging with fresh lithium chloride solution is essential. Typically, the dew cell, when equipped with a 100-ohm resistance thermometer element, has a time constant of 12 to 15 minutes, but miniaturized sensors with thermistors are much faster.

Cooled-mirror dew point instruments offer greater accuracy and faster response characteristics. Typically, the accuracy is $\pm 0.5^{\circ}\text{C}$ while the resolution is 0.1°C . Unlike dew cell sensors which the user must house in a weather shield, cooled mirror devices are supplied in a housing and may include sensors for both dew point and temperature. The latter must not be used for T or ΔT measurements, but may be used for calculating relative humidity. In some cooled mirror instruments the "standardizing" process is automatic. This procedure involves heating the mirror surface periodically to clear it of frost and dew deposits. In others standardizing is a manual operation. Occasional cleaning of the mirror surface is necessary, especially in polluted atmospheres. The cooled mirror technique is considered a fundamental measurement technique.

Psychrometers which incorporate a dry bulb and a wet bulb are a basic measurement technique. For checking, the sling psychrometer, or better, the motor-operated psychrometer is an easy-to-use instrument but requires some skill and care. The motor-aspirated unit of the Assman type can be obtained with specially calibrated thermometers

that have a resolution of 0.05°C and a basic accuracy of 0.1°C. Psychrometers built with platinum wire sensors, thermistors, etc., have been used on some tower installations but users experience maintenance problems and operational problems, especially in near-freezing conditions. The psychrometric technique is not recommended for operational towers installations but may have limited applications at research sites.

2.4 Pressure

For diffusion calculations, pressure can be measured with almost any pressure instrument. It probably could even be estimated from a standard atmosphere and the site elevation. If pressure is measured in a machine processable data base, an accuracy of ± 1 kPa (10 mb) is adequate. The expression for the representative period may be a single instantaneous sample (p) or the arithmetic mean of any number of samples ($\bar{p}$).

2.5 Precipitation

There are two basic designs of recording precipitation gauges, identified by the principle on which they operate: the weighing gauge and the tipping bucket gauge. With modifications, the weighing gauge can be adapted for remote transmission; the tipping bucket requires no modification.

In both of the gauges, precipitation can be resolved to 0.2 mm, or 0.01 inches, water equivalent. Unlike indicating gauges which require a measuring stick calibrated to resolve amounts to 0.2 mm and/or 0.01 inches, recording gauges are advantageous because they document the total amount of precipitation and the beginning, ending, and rate of precipitation, when the amount exceeds the resolution of the instrument.

The weighing gauge is usable for collecting frozen precipitation, but in below-freezing conditions, the bucket must be charged with antifreeze as well as an evaporation-retarding oil in keeping with accepted practice. The use of a shield and/or the installation of the

gauge in a sheltered location is essential for the collection of representative snow samples and is desirable year-round. The NWS reports (Weiss 1961) that with a 20 mph wind, the catch of snow in a gauge can be reduced by 50%.

Tipping bucket rain gauge accuracies for liquid precipitation decrease as a function of rate-of-fill. Accuracies are 1% for rainfall rates of 1 inch/hour or less; 4% for rates of 3 inches/hour; and 6% for rates up to 6 inches/hour. Greater inaccuracies occur when the buckets are not properly sited. Heating systems for tipping bucket gauges used in below-freezing conditions are of limited value; they must be used with care and with thermostatic control to avoid evaporation of the sample.

The automatic wet/dry precipitation collector represents a specialized type of nonrecording gauge designed for acid-rain studies and other programs involving the chemical or radioactive analysis of precipitation. A sensor that detects the onset and cessation of precipitation automatically moves a lid or cover over the collector to minimize evaporation. The significant factor in this type of collector is the ratio between the amount of precipitation and the polluting ingredient. Dry fallout is also of interest for some studies.

It should be emphasized that while the siting of a gauge is important, the representativeness of a measurement at one location must be weighed against multiple or network measurements.

2.6 Solar Radiation

Generally, solar radiation is measured in units of energy flux, either in W/m^2 or cal/cm^2-min . It is also described in terms of percent of sunshine and effective cloud cover. When solar radiation is measured within specific narrow-band wavelengths, it is useful for determining the turbidity and amount of precipitable water—indices of atmospheric pollution and determining the potential for photochemical reactions. Broad-band measurements of energy flux are of significance in the processes related to turbulence and diffusion.

Short wave radiation is represented by wavelengths less than 4 micrometers (μm), long wave radiation by wavelengths from 4 μm to 100 μm .

Both total solar and net radiation measurements have been used in determining atmospheric stability. Since both are relatively inexpensive and easy to install and maintain, installing one set of sensors should receive serious consideration. One set of measurements is likely to be representative of a large area unless there are significant variations in topography or vegetative cover.

Siting of the sensor(s) must allow for an unrestricted view of the sky in all directions during all seasons, including the lowest solar elevation angle reasonably possible. Sensor height should be within 2-5 m. The surface below the net radiometer must be representative of a broad area around the site.

Pyranometers measure the total sun and sky shortwave radiation. They incorporate either a thermopile or a silicon photovoltaic cell as a sensor. The silicon cell covers wavelengths from 0.35 to 1.15 μm , the thermopile from 0.28 to 2.80 μm . This is the range covered by most NWS measurements. Not all pyranometers are temperature-compensated but those so designed are preferred. Standard units are compensated within $\pm 1.5\%$ over the range -20° to $+40^{\circ}\text{C}$. The sensitivity of a typical 48-junction thermopile "black and white" pyranometer is 11 μV per W/m^2 , or 7.5 mV per $\text{calorie}/\text{cm}^2\text{-min}$. Since absolute values of solar radiation have limited value, it is important to translate the data to integrated figures, typically for 1-hour periods.

When gathering data on problems involving solar radiation as a important factor in photochemical reactions, the spectral pyranometer, designed with two hemispheres, is the better selection. The substitution of one of the hemispheres with a Schott glass filter in a defined wavelength permits measurement of yellow, orange, red, or dark red bandwidths. For problems related to ozone, an ultraviolet radiometer for the spectral range of 0.295 to 0.385 μm would be the better choice. The choice of instrument depends on the application.

Net radiometers are designed to measure both the incoming (mostly short wave) radiation and the outgoing (mostly long wave) radiation.

Typically, they cover the wavelengths from 0.3 to 60 μm . Polyethylene hemispheres are used to cover and protect the thermopile sensors. Most thin hemispheres must be internally pressurized to maintain their shape and to minimize condensation. In a recent design change, the hemispheres were constructed of heavy-duty plastic which attenuates the signal by 4% but has the advantage of eliminating the need for external sources of nitrogen gas. An in-line dessicator tube is sufficient to handle the condensation problem. The sensitivity of one typical domestic-made net radiometer is 5 μV per W/m^2 ; an imported unit has a sensitivity of 0.5 $\text{mV}/\text{mW}/\text{cm}^2$. The time constants of these units are 30 and 60 seconds, respectively, with typical signal ranges of -5 to 10 mV . The negative value represents outgoing radiation; the positive value represents incoming radiation.

The installation of a net radiometer is quite different from that of a pyranometer. The radiometer is installed with the aid of a bubble level on an arm that is south-facing, usually about 1 meter above the ground surface so that there is an unobstructed view of the total incoming and total outgoing radiation. By contrast, pyranometers should be located on a level roof mount so that no obstruction casts a shadow on the sensor at any time. The hemispheres on the net radiometers and pyranometer must be kept free of foreign material and dust.

3. REMOTE MEASUREMENTS

3.1 Convective Mixed Layer Height

The height of the convective mixed layer is the height to which material released in the atmosphere's boundary layer will spread under unstable and neutral conditions. This mixed layer is capped by a region of stable temperature profile, usually by a profile so stable that the temperature actually increases with height (an inversion layer). Then the top of the mixed layer can be measured if the base of the capping inversion can be identified.

In principle, it should be possible to detect the inversion base by measuring the temperature variation with height using in-situ sensors mounted on aircraft, free balloons, and tethered balloons. This approach, though straightforward, requires much manpower, is intermittent and expensive if monitoring is to be carried out for a long period. An alternate approach, which lends itself to unattended continuous operation, takes advantage of the scattering properties of the mixed layer-capping inversion interface. This interface is a region of sharp gradients in temperature and in humidity and aerosol concentration. Remote sensing techniques (sodars, lidars, and FM-CW radars) provide echo signatures from which h_c can be extracted; sodars are the most economical and commercially available.

The key to interpreting backscatter returns from remote sensors is the recognition that the sharpest inhomogeneities in temperature and humidity are found at a height slightly above the mixed layer—capping inversion interface. The base of the strongest echo layer is therefore used as the reference level for h_c . These returns often show gravity waves and gust fronts (such transients at the capping layer must be recognized when interpreting the representativeness of single soundings with in-situ sensors).

Vertical profiles of temperature are readily accomplished with a light plane spiraling up and then down. A fast response temperature sensor is installed for recording temperature versus pressure altitude

by chart or manually. Helicopters do the job in regions where airspace is more restricted. Small radio-controlled drone aircraft with telemetering temperature and pressure sensors have been used for the same purpose.

A type of radiosonde balloon telemetering temperature is commonly used. Altitude cannot be accurately ascertained from time and ascent rate, so either double theodolite observation or a telemetering pressure system must also be used. Since standard radiosondes have poor vertical sampling rates, slow rise balloons with appropriate sensors are used for deriving high-resolution temperature profiles. Tracked balloons also yield wind data.

Tethersondes, carrying aloft sensors whose readings are telemetered to the ground, are convenient to use in moderate and light wind conditions in regions where they are not an aviation hazard. Temperature profiles are easiest to obtain, but turbulence can also be measured. The profiling is most commonly performed by raising and lowering the balloon, but it can be done by using multiple sensors spaced below a stationary tethered balloon.

A monostatic sodar with vertically pointing beam, with time-height echo amplitude displayed on a facsimile recorder, is widely used to find h_c . It also shows the overall situation in the lower atmosphere, showing multiple layers, clarifying the evolution of mixing processes, etc. A shearing echo is recognizable by being predominantly horizontal. Its presence is attributable to small-scale temperature variations associated with turbulence within a stable region. It designates a blocking layer from the standpoint of vertical diffusion—its turbulence is of a scale and intensity and intermittency which is ineffective in causing rapid vertical material transport. During unstable convective conditions, the lower portion of thermals are identifiable on the record by "spikes" rising from the surface, while the shearing echoes delineating mixing height ride horizontally (or in gentle waves) overhead. Objective rules have been developed which permit h_c to be derived, approximately hourly, by a human operator. Automatic pattern recognition might permit the task

to be done automatically, but this is not yet a proven technique. Numerous comparisons between h_c ascertained by sodar and by temperature profiles have shown satisfactory agreement between the two methods—generally within 50 m. The upper heights at which h_c can be observed by sodar depend on the meteorological situation, the characteristics of the sodar unit, and the ambient noise. A height of 500 m is usually reached, 800 m is often reached, and 1,000 m is sometimes reached. The period of greatest uncertainty in h_c estimation is the three hours prior to sunset when the capping inversion either disappears or becomes too weak to be detected. If the more advanced Doppler sodar system is available, yielding directly turbulence intensity versus height, chart interpretation of h_c is not necessary.

FM-CW radar presents a similar facsimile display from which h_c can be found. The echos are primarily from humidity variations. The radar reaches as high as needed for boundary layer monitoring, but the device is specialized, expensive, and not commercially available.

A backscattering lidar system records echos from aerosol particles, and displays them on a facsimile recorder analogous to sodar and radar. Since high aerosol content is characteristic of the mixed air mass (especially its top) and low content characterizes the region aloft, the interface region and h_c can easily be found on the display. The lidar reaches as high as needed. The device is specialized, expensive, and not in commercial production.

All these methods will operate in altitudes unreachable by normal towers. Aircraft and balloons readily achieve any height desired. Tethersondes are limited by practical considerations of lift, payload and the wind drag of balloon, instruments, and tether, as well as by Federal Aviation Administration regulations. Heights of about 300 m are very common, 1,000 m heights are sometimes handled, and greater heights are feasible if economically justifiable. Sodar is generally satisfactory to above 500 m, and sometimes beyond 1,000 m—with the height increasing as the technology evolves. The other indirect probes can reach beyond 2 km.

3.2 Mechanical Mixing Layer Height

In a stably stratified boundary layer there is often enough wind shear to produce vertical mixing over its entire depth. The height to which the mixing operates is not determined solely by the temperature profile, but rather, in a complex way, by both the temperature and velocity fields, and is influenced by surface roughness as well. The nonlinear interactions can make the situation nonstationary.

The height of the mechanical mixing layer is best defined by the vertical profile of the vertical component of turbulence. The vertical profile of temperature represents a satisfactory alternative, if interpreted correctly. The strongly stable portion of the lower boundary layer designates a region into which cold surface air has been mixed; the temperature profile indicates that there was mixing into this region, but does not verify that mixing is going on at the present moment. When considering continuous releases and hour-long pollutant concentrations, the time variations of mixing properties are not of primary importance. Consequently, the profiles of turbulence or temperature can give the information needed on the height to which diffusion reaches upward from the surface. Conceptually, all the techniques available for ascertaining h_c can be applied to finding h_m , although the aircraft method and free balloon method are scarcely "practical" when dealing with height only up to 50 m or so. For low altitudes, the use of instrumented towers is much more feasible than they are for the h_c case. Tethersondes can conveniently yield temperature profiles, if intermittent data are satisfactory.

Sodar records can be interpreted to give h_m . Here, the upper boundary of the strong echo region (rather than the base) is assumed to be the top of the mechanical mixing layer. Conventional sodars, which have been developed to emphasize the higher altitudes, can only show surface-induced mixing rising above the minimum range of about 35 m. It is anticipated that better information to heights down to 10-15 m can be derived from units tailored to the purpose of finding

h_m . The units would operate at high frequency, with shorter pulse lengths, and the facsimile display would utilize an expanded vertical scale. Interpretation of h_m from sodar is occasionally ambiguous at this stage of development of the technique—primarily because of the complex nature of the phenomenon being observed.

3.3 Flow Field Aloft

All the probing devices discussed for finding h_c can conceptually be adapted to the more demanding task of monitoring the flow field aloft (mean and turbulence). Diffusion modeling is not limited to heights below h_c , since effective stack heights can exceed h_c , and diffusion through higher layers can also be important in long-range transport.

For case study projects, instrumented aircraft can be particularly effective. Aircraft such as those developed and operated by National Center for Atmospheric Research combine flow probes with inertial navigation systems to measure mean wind as well as turbulence in all components and all important scales. An aircraft's mobility allows the acquisition of data throughout a large three-dimensional volume, with the limitation that flights cannot ordinarily be below 150 m (with much higher threshold, because of safety, in complex terrain). The same airplane that monitors the atmosphere can also monitor a pollutant plume or tracer.

Ascending free balloons tracked by double theodolite are useful in finding the wind field—to the extent that a spot observation represents events over a finite time interval. Tracking of "zero lift" balloons can yield information on turbulence and flow trajectories, but the technique is extremely difficult. Tracking of superpressure balloons is a more applied technique, and yields data on flow trajectories. Since the balloon does not exactly follow an air parcel when vertical motion is involved, the results must be interpreted cautiously.

For a complex terrain research program, a network of double-theodolite tracked balloons could be used for finding the wind field. A network of tethersondes with wind sensors can also be used. Turbulence sensors can also be added to monitor mixing factors directly. Operation of a network of highly instrumented tethersondes is a formidable undertaking.

Wind and turbulence fields can also be monitored by Doppler versions of the indirect probing techniques: sodar, FM-CW radar, and lidar. Other radars have occasionally been used to observe the motion of clear air into which chaff has been introduced to give back-scattering. The relative economy of sodar makes this technique a good candidate for observing the flow field for both case study research programs and long term monitoring programs for the altitudes pertinent to high plume dispersion.

Recent studies comparing various flow measuring devices with the BAO 300 m instrumented tower at Boulder, Colorado, have shown that accuracies of Doppler sodar systems are within 0.5 m/sec for measurement of wind components aloft. Also, there is initial evidence that certain velocity variations can be continuously monitored directly giving some turbulence quantities of importance in diffusion modeling. Investigators are trying to derive temperature gradient information (only to the broad accuracy limits required when temperature gradient data are used in plume rise equations) from profiles of wind and turbulence. If successful, Doppler sodar may be capable of providing all the meteorological inputs needed for high stack dispersion model calculations.

There are two basic types of Doppler sodar systems: monostatic, where all antennas are located adjacent to each other (sometimes mounted on one trailer) and bistatic, where antennas are separated horizontally by distances comparable to the maximum height of observation. In complex terrain, not only must the logistics and complexity of installation be considered, but also the problem that echoes from nearby elevated terrain can swamp the echoes from atmospheric scattering unless the antenna sidelobe suppression is well

handled. Doppler sodar appears capable of giving mean and turbulent flow information well suited to diffusion modeling, routinely to heights of 500 m, and sometimes to heights above 1,000 m.

Another remote sensing technique for indirect probing is the two-ended laser anemometer. It does not have an extensive history for validation, but does provide a method for obtaining integrated wind speed components normal to the path along path length. It is used to measure wind speeds across valleys and will determine mean speeds well under 1 m/sec.

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